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Design and development of flexural plate wave biosensors

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Design and Development of Flexural Plate Wave Biosensors

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Abstract

This thesis presents the design and development of a flexural plate wave sensor. Flexural plate wave sensors are known for their good sensitivity and their possible application as biosensor as they are able to operate in a liquid environment. However, in the same time they are known for their difficult fabrication. The sensor's model is fully explored and material properties are investigated. There is concluded that a high Young's modulus, low Poisson's ratio and low density are the best material properties for a good mass-sensitivity of this device. Therefore nano-crystalline diamond is chosen as waveguide layer and aluminum nitride is used as piezoelectric material. However platinum has a disadvantage in its density, it is chosen over aluminum as metal layer for its easier processing.

Masks are designed to micro-process 67 flexural plate wave sensors on 4 inch wafers. Each device has its own design parameters with varying length, width and wavelength. For each of these devices, parameters as phase velocity, frequency and sensitivity in air and liquid are simulated. Operating frequencies are in the low megahertz range, and highest simulated sensitivity (in liquid environment) is 27.7 m²/kg. Highest sensitivity (and frequency) is obtained for devices with the lowest wavelength.

Processing is discussed together with many encountered problems. A larger problem faced was the quality of the piezoelectric aluminum nitride. To investigate this material a new design was made to process cantilever beams with a layer of this piezoelectric material. By applying a voltage over the beam, the tip will deflect, and the piezoelectric coupling coefficient (d₃₁) can be determined.
Acknowledgements

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Introduction

1.1 Biosensors

A biosensor is an analytical device which converts a biological response into an electrical signal. The term "biosensor" is often used to cover sensor devices used in order to determine the concentration of substances and other parameters of biological interest even where they do not utilize a biological system directly. Research and development in this field is wide and multidisciplinary, spanning biochemistry, physical chemistry, electrochemistry, electronics and software engineering. The physical part of the sensor is the transducer, where some "event" is transduced into an electrical signal (Figure 1.1). In this report this event will be a mass change on the surface of the sensor.

It is said that this will become the "bio-era", because there is a strong rise in the demand for sensors that are able to detect low concentration levels of specific molecules. This is, and will be a century where lots of efforts are put in the development of bio-products, e.g. biosensors for food safety, drug delivery or testing et cetera. The global market for biosensors has increased rapidly, and continues increasing in the 21st century. Although the potential market for biosensors is known to be very large, the commercialization of the numerous biosensors has been slow except rare cases including glucose monitoring, single analyte enzyme electrodes for food industry and biological oxygen demand for water. The limit has been imposed by a lack in the desired performance characteristic of the biosensor in terms of sensitivity, dynamic range and reproducibility.

A wide variety of transducing systems are suited for detection, most common principles are shown in Figure 1.1. As a mass sensitive device the Quartz Crystal Microbalance is the most familiar, but the other acoustic-wave devices are promising in sensitivity, including the flexural plate wave device discussed in this report.

1.2 Brief outline of this report

In Chapter 2 a general overview and introduction of the available acoustic sensors together with a historical perspective for the main-stream acoustic wave devices is given.
Chapter 3 goes into a detailed description of the flexural plate wave device and shows the basic modeling for a conventional design.
Chapter 4 discusses the model presented in Chapter 3, and tries to obtain the optimal design parameters for the flexural plate wave device.
Chapter 5 describes the used thin film microfabrication techniques, such as deposition and patterning.
In Chapter 6 the design of the processing mask is shown, together with the process flow.
Chapter 7 describes all steps needed to obtain the piezoelectric constant of the AlN available at IMEC.
Chapter 8 handles the encountered processing problems, illustrated with pictures, and comments on solutions.
Finally a discussion of the obtained results and conclusions are combined in Chapter 9.
2

Acoustic Wave Sensors
-State of the Art-

2.1 Introduction

A sensor is to provide us with an output signal (mostly electric) in response to some input quantity, whose frequency represents the value of the input quantity. The range of input quantities can be large, including physical quantities such as the mechanical properties of thin films, and chemical and biological quantities such as the concentrations and identities of unknown species in air or liquid media.

Inside a typical sensor a process of transduction takes place, converting the input event into an electrical signal. Sensors are characterized in many different ways. Their sensitivity is a measure of the magnitude of the output signal produced in response to an input quantity of given magnitude; their resolution is a measure of the minimum charge of input quantity to which they can respond; and their selectivity characterizes the degree to which they can distinguish one input quantity from another. The biosensors selectivity can be very high. It may include a biorecognition element as a "front end" which responds to only one biological substance. This element may contain particular molecules that react with only one other type of molecule (e.g. antibody-antigen reaction). Exploiting this bioselectivity can permit detection of very low concentrations of substances in a very dense background of other molecules [2].

The last couple of decades there is a growing interest in small and cheap microsensors. In contrast to integrated circuits, the sensor has not evolved much and they are still fairly large and expensive devices. One possible way to obtain this goal is based on acoustics. More explicitly, the use of elastic waves at frequencies well above the audible range propagating in specially designed solid sensing structures.

The first acoustic sensor was the quartz crystal microbalance (QCM) designed in the 1950s [2]. The QCM employed a slightly modified quartz crystal made initially to stabilize the frequencies of radio transmitters. The modification that permitted it to be used for chemical sensing was the addition of a sorptive film on the crystal. Another device was made in the late 1970s when Wohltjen and Dessy [52] realized that chemical vapor sensing could be accom-
plished with a device designed originally for processing purely electrical signals, the surface-acoustic-wave delay line. In this device, acoustic waves are generated and detected with the comb-like conducting structures shown at each end of the device; a piezoelectric material in the device substrate converts energy between electrical and mechanical forms at the comblike structures. More recently, two other sensors were introduced that employ similar principles but exploit different modes of elastic wave propagation: the acoustic plate mode device and the flexural plate wave device (FPW), which is further explored throughout this report. The four most common acoustic resonators are shown in Figure 2.1.

Figure 2.1: Schematic sketches of the four common types of acoustic resonators and their wave propagation modes. The particle displacement is indicated by a black arrow, and the direction of the wave propagation by an open arrow. TSM: thickness-shear-mode resonator, also known as the quartz crystal microbalance technique; FPW: flexural plate wave resonator; SAW: surface acoustic wave resonator (two port delay line) and SH-APM: shear horizontal acoustic plate mode resonator [23].

These devices are conveniently small, relatively inexpensive, quite sensitive, and inherently capable of measuring a wide variety of different input quantities. It is because of these far-reaching characteristics that this research was performed.

2.2 Acoustic Wave Sensors

The acoustic sensors operate over a frequency range of three orders of magnitude, from less than 1 to more than 1000 megahertz, as indicated in Figure 2.2. All of these sensors “sense” by producing a change in the characteristics of the path over which the acoustic waves travel. There are several ways of
2.2 Acoustic Wave Sensors

Figure 2.2: The spectrum of acoustic waves covers roughly 14 orders of magnitude. The frequency range of the 4 most important resonators range in operation between 1 and 1000 megahertz [23].

detecting such changes. One way is the “active” approach in which the sensor is part of an electronic oscillator circuit, so that a change in the characteristics of the acoustic path causes a change in the frequency of the oscillator. The alternative approach for getting information from these acoustic sensors is to measure the sensor characteristics passively; that is, to supply an external electrical test signal and determine the response of the sensor to that signal. For example by measuring the attenuation of the test signal the viscosity of a fluid that contacts one of these sensors can be determined.

Acoustic waves can be distinguished in two groups: Bulk acoustic waves (BAWs) and Surface acoustic generated waves (SGAWs). The acoustic family is fairly large and represented in Figure 2.3. The SGAWs travel along or near a free surface such as surface acoustic waves (SAWs).

2.2.1 Bulk acoustic waves

Bulk acoustic waves travel in the bulk of a material and present interaction at opposite surfaces. BAWs were the first to be developed as acoustic waves based sensors, used for detection of gases. A representative device is the quartz crystal microbalance (QCM) which was firstly developed for monitoring of thin films in microelectronics [15]. These devices are also used as biosensors, e.g. for antibody-antigen monitoring. Shear waves are used for minimizing power dissipation in fluid supporting the biochemical species.
Figure 2.3: The acoustic wave family. This family is fairly large and has to be distinguished between bulk acoustic waves (BAW) and surface generated acoustic waves (SGAW) [15].

The sensor is based on a resonance principle, a stationary wave is generated and maintained in a plate with thickness multiple of a half-wavelength. This mode is called thickness shear mode (TSM). The bulk acoustic wave phase velocity and the boundary conditions (electrical and mechanical at surfaces) determine the resonance frequencies. Although in principle any kind of piezoelectric material can be employed, the QCM uses the AT-cut of quartz. This cut has been studied for more than 50 years; it provides a shear wave vibration with a resonance vibration that has the advantage to be stable in a large temperature domain.

QCM is called microbalance due to the frequency decrease when loaded by a mechanical charge at its surfaces. The QCM exhibit best sensitivity for the first modes of resonance and for higher operating frequencies. A very sensitive device could then be obtained with a very small thickness. However, realization and holding problems limit the maximum sensitivity that can be obtained.

2.2.2 Surface acoustic waves

Surface acoustic waves (SAWs) are known since Lord Rayleigh suggested that they “play an important part in earthquakes, and in the collision of elastic solids.” For that reason, surface acoustic waves are equally named Rayleigh waves. These waves have displacements that decay in an exponential way in depth beneath the surface. Almost all of the elastic energy is concentrated
2.2 Acoustic Wave Sensors

within a distance of the order of a wavelength below the free surface. The particle motion on the surface and at each depth is elliptical and entirely contained in the plane perpendicular to the surface. Rayleigh waves know successful applications in the telecommunications with development of filters and delay lines. The deposition of interdigital transducers at the surface of piezoelectric media has widely opened the field of investigations for the gigahertz frequency range. They were also successfully applied as sensors: for example temperature, pressure, acceleration, (high) voltage, polymer phase transitions and gas concentration sensor. However they are rarely used for biosensing applications. The literature reports sometimes SAW biosensors although the presented devices do not apply the SAW properties; actually those sensors support other types of waves (Acoustic Plate Modes or Love Modes) and can not be considered as pure SAW devices.

Bleustein-Gulayev (BG) waves are pure shear horizontal waves propagating in piezoelectric substrates. As any Shear Horizontal (SH) waves, BG waves have a high potential for fluid-sensing applications. They have a single electrical component that is perpendicular to the crystal plane. The waves are sensitive to electrical and viscous properties. The BG waves can not propagate in $\alpha$-SiO2, lithium niobate, nor in lithium tantalate. Some materials that are candidates to BG are lithium iodate (LiIO3), lithium borate (Li2Bi4O7), bismuth germanate (Bi12GeO20) and KTP (KTiOPO4). Up to now, only the latter has received interest as immunosensor.

Pseudo-SAWs propagate along the surface of piezoelectric substrates and attenuate in the direction of propagation. They have a small component of propagation directed to the bulk of the substrate. Therefore they are also called leaky-SAW. They appear only for certain orientations and have a phase velocity higher than that of the SAW. For some material and cut combinations, the attenuation may be very small or almost zero, for instance in the $Y-$ rotated $X-$ propagating cut of lithium niobate and lithium tantalate. Furthermore, the leaky-SAW in those latter materials has almost a shear horizontal component. The major drawback of the pseudo-SAW is interference from the spurious bulk modes [15].

2.2.3 Plate modes

Acoustic plate modes (APM) are waves excited in a plate. These modes may have displacements that are either transverse to the propagation direction (shear horizontal, SH-APM, and shear vertical, SV-APM) or in the propagation direction (longitudinal, L-APM). In terms of liquid-sensing applications, SH-APM are the most attractive since they do not present coupling with the liquid. That means no energy is radiated in the liquid. The plate can support a large range of acoustic modes, each one with its own frequency. Any perturbation of the top or the bottom boundaries of the piezoelectric plate modifies the modes in the plate. In any case, for instrumental reasons, it is more efficient to isolate one mode and then track this mode as the boundary conditions change. Preferentially, this mode should be sufficiently removed from neighboring modes so that interference can not occur. The APM device uses interdigital transducers
(IDTs) in order to launch the acoustic modes. These IDTs are on the backside of the sensor and so they are not in contact with the liquid.

Lamb waves are considered as the interference between SAW propagating along the parallel faces of a plate. As the thickness of a plate is greater than a few wavelengths, two independent SAW's can propagate on each face; as the thickness is reduced to a few wavelengths the two waves interact and result in two Lamb-type plate modes. The even (symmetric) mode behaves like the SAW and the odd (anti-symmetric) mode velocity approaches zero as the plate thickness is decreased. Very thin membranes can be fabricated using micromachining techniques. Therefore Lamb wave sensors may be used as fluid phase sensors and they have been shown to be extremely sensitive. However, they are hard to produce due to device fragility and difficulties in reproducibility, which make them less explored for biosensing applications. Detailed information on Lamb wave based devices can be found in Chapter 3.

2.2.4 Surface skimming bulk waves

Since most SAWs have significant displacement components perpendicular to the crystal surface, they radiate energy into the adjacent liquid, therefore limiting their application as biosensors. Interdigital transducers are known to excite a spectrum of shear and longitudinal bulk waves that propagate into the piezoelectric medium. Usually, reflections of the bulk waves from the bottom of the sensor occur and interfere with the SAW signal, leading to a further decrease of the sensor response. In some materials, these waves propagate parallel or nearly parallel to the piezoelectric surface and reach the output IDT without reflecting from the bottom. These waves are named surface skimming bulk waves (SSBWs). For sensor application, a reasonable coupling coefficient should be present while the other bulk waves and the SAW should be low to avoid interference. The SSBW must be horizontally polarized for sensor application. If a layer is placed between the input and output transducers, the shear SSBWs convert to a waveguide mode called Love mode. This occurs only if the shear acoustic wave velocity in the layer is less than in the substrate. Several modes can exist as function of the layer thickness. For biosensing applications, single mode operation is better since the first mode is more sensitive.

2.2.5 Comparison

For biosensors, the specific species that need to be sensed are usually supported in a liquid medium. The presence of the liquid medium makes all the sensors supporting non pure shear waves unavailable for biosensors. Energy losses at the interface between the device supporting the acoustic wave and the liquid supporting the biological species can follow two paths. The first one is a coupling by a non pure shear horizontal component, i.e. normal displacement that generates a compressional wave into the liquid. The second one occurs when the wave phase velocity is greater than the compressional velocity in the liquid, causing generation of a leaky wave into the liquid and thus energy dissipation.

The use of Rayleigh devices is directly suited for biosensor applications.
The requirements are encountered by use of devices that present only viscous coupling with the liquid. Effectively, this coupling undergoes less attenuation. Therefore, the QCM, SHSAW (BG and pseudo-SAWs), SH-APM, Lamb modes and Love modes are suited for biosensor applications. Those devices and the location of the liquid cell is represented in Figure 2.4 (courtesy of A. Campitelli [4]).

![Figure 2.4: Configuration of biosensors. Drawings include the presence of the electrodes for transducing and position of the liquid cell. The liquid cell contains the biochemical species and is a part of a more complex system of liquid delivering around the biosensor [4].](image-url)
3.1 Introduction

In a flexural plate wave (FPW) device, an acoustic wave is excited in a thinned membrane. It can sense quantities that cause its phase velocity, \( v_p \), to change. A unique feature of the FPW is that it can be dimensioned in a way that its phase velocity is lower than that of most liquids, which lie in the range from 900 to about 1500 m/s. When the FPW device contacts such a liquid, a slow mode of propagation exists in which there is no radiation from the plate. Thus, it is a good candidate for biosensing and chemical sensing in liquids. Because the "plate" of a FPW device may be only a few micrometers thick, the mass per unit area of the thin plate can be increased significantly by mass-loading produced by the adsorption of chemical vapor molecules on the plate. This causes the phase velocity of an ultrasonic wave propagating on the plate to decrease. Other effects that can be measured in fluid-loaded FPW devices by monitoring the phase velocity, are changes in the density of a fluid on the plate and the attachment onto the plate of protein molecules, cells and bacteria from a liquid that contact the plate.

An opposite effect occurs if the tension in the thin plate is increased, for example, by establishing a differential gas pressure across it, by applying a force on the plate, or by bending the frame that surrounds it. The increased tension causes the real part of the phase velocity to rise. The most obvious advantages and disadvantages of the FPW technique are shown in Table 3.1.

<table>
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<td>Fabrication cost</td>
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<tr>
<td>Low operational frequencies ( \rightarrow ) simplifies electronics (low MHz)</td>
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<tr>
<td>High sensitivity</td>
<td>Device fragility</td>
</tr>
<tr>
<td>Higher amplitudes ( \rightarrow ) better mechanical coupling</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: Pro's and contra's of the FPW technique.
3.2 Flexural Plate Waves

3.2.1 Introduction

In the simplest case of an elastically isotropic plate there is an infinite set of waves that can exist. These are known as Lamb waves, after Sir Horace Lamb who published their first detailed description [27]. They are best described as waves that propagate along an infinite elastic plate with free boundaries. The waves divide naturally in two sets: symmetric waves (denoted by $S_0$, $S_1$, ...) whose particle displacements are symmetric about the neutral plane of symmetry, and anti-symmetric waves (denoted by $A_0$, $A_1$, ...) whose displacements have odd symmetry about the neutral plane. For sufficiently thin plates only two waves can exist: the lowest-order symmetric mode ($S_0$) and the lowest-order anti-symmetric mode ($A_0$). These are shown in Figure 3.1. The plate mode that is emphasized here, is the $A_0$ mode in which the elements of the plate undergo flexure as the wave propagates. The shape of a plate during propagation of this flexural mode has been likened to that of a flag in the wind.

For very small thickness-to-wavelength ratios, the phase velocity of the $A_0$ mode approaches zero asymptotically. As $d/\lambda$ increases, $v_p$ increases, finally becoming asymptotic from below to the surface-wave velocity for the medium. This rise is due to the increased effective stiffness of the medium as the thickening plate is required to assume the sinusoidal wave shape. The phase velocity of the $S_0$ mode is maximum for a very thin plate, and it falls as $d/\lambda$ increases, finally becoming asymptotic from above to the surface-wave velocity for the medium. The approach to the surface-wave velocity as the plate becomes thick is to be expected, as a surface wave can be represented as a superposition of antisymmetric and symmetric waves.

3.2.2 Flexural plate wave model

The most applications of the FPW device are in the region of very thin plates ($d/\lambda \ll 1$). In this region plate-mode delay lines whose phase velocity is below the velocity of sound in water can be fabricated. Since the frequency of operation, $f$, for a given wavelength, is given by [2]:

$$f = \frac{v_p}{\lambda}$$

(3.1)

this frequency is low for low phase velocity. A low operating frequency is an attractive feature as it implies the use of relatively inexpensive associated electronic circuitry. Finally it is possible, in the thin-plate regime, to approximate

---

1Sir Horace Lamb (November 29, 1848 - December 4, 1934) was a British applied mathematician and author of several influential texts on classical physics, among them Hydrodynamics (1895) and Dynamical Theory of Sound (1910). He studied at Cambridge University and in 1872 was 2nd Wrangler in the Mathematical Tripos. His professors included James Clerk Maxwell and George Gabriel Stokes. In 1883 he published a paper in the Philosophical Transactions of the Royal Society applying Maxwell’s equations to the problem of oscillatory current flow in spherical conductors, an early examination of what was later to be known as the skin effect [Wikipedia, 2005].
3.2 Flexural Plate Waves

Figure 3.1: Schematic of the phase velocity of flexural plate waves vs ratio of plate thickness, \( d \), to wavelength, \( \lambda \). The phase velocity of the anti-symmetric mode (\( A_0 \)) reaches zero as \( d/\lambda \) does, which makes the FPW device interesting for in-liquid measurements.

the phase velocity quite well by the simple asymptotic expression [2]:

\[
V_p = \left( \frac{B}{m_a} \right)^{\frac{1}{2}}
\]

where \( B \) is the bending stiffness of a homogeneous, elastically isotropic plate and \( m_a \) is the mass per unit area of the plate. For an \( A_0 \) Lamb wave in a tension-free plate, the bending stiffness takes the form [46]

\[
B = \frac{2\pi}{\lambda}^2 \frac{E}{1 - \nu^2} \frac{d^3}{12}
\]

where \( d \) is the plate thickness, \( E \) is the actual Young’s modulus and \( \nu \) the Poisson’s ratio for the material.

The FPW device employs interdigital transducers (IDT’s) and piezoelectric coupling to generate and detect the waves. The successful development of the IDT by White and Voltmer [50] allowed direct piezoelectric coupling to surface acoustic waves. An IDT consists of a pair of overlapping, interspersed “finger” arrays. Normally there are an equal number of fingers on each half of the IDT, with the finger width equal to the finger spacing. When a potential is applied across the IDT, the substrate undergoes a periodic deformation. When an alternating potential is applied, an acoustic wave is launched which propagates away from the IDT in both directions and perpendicular to the long axis of
the IDT fingers. The acoustic wavelength will then be determined by the IDT geometry and finger spacing $FS$.

$$\lambda = 4FS$$  \hspace{1cm} (3.4)\]

![Diagram of IDT generation of a wave in a plate](image)

**Figure 3.2:** Schematic representation of IDT-generation of a wave in a plate. A top-view of the implementation of IDT's in FPW is presented in Chapter 6 Section 6.1.

Models are made to predict the behavior of the waves based on simple beam equations [49][2][28][42][41]. A more detailed solution is presented by Weinberg *et. al.* [44]. Weinberg *et. al.* derived in [43] the structural rigidity and piezoelectric torques for multilayer plates, as used in the FPW device. The bending torque generated by an electric field across the piezoelectric layer is:

$$M_p = \frac{E_p \Delta y_m A_p d_{31}}{h_p (1 - \nu_p)}$$  \hspace{1cm} (3.5)

where $M_p$ is the torque per unit voltage across the piezoelectric layer; $\nu_p$ is Poisson’s ratio: the term in $\nu_p$ accounts for plates versus thin beams (results for a slender beam can be obtained by setting $\nu = 0$); $d_{31}$ is the piezoelectric coupling coefficient; the subscript $p$ presents the piezoelectric layer; $\Delta y_m$ is the distance between the piezoelectric material’s center of area and the diaphragm’s neutral axis for torque inputs; $E$ is the Youngs’s modulus; $h$ is the layer thickness and $A$ is the layer cross-sectional area (thickness times width). A concept well known in conventional stress analysis, is that the neutral axis for torque inputs is the weighted center of

$$\sum_{i} y_i E_i A_i = \sum_{i} \frac{E_i A_i}{1 - \nu_i^2}$$  \hspace{1cm} (3.6)

where $y$ equals the vertical distance from the center of area to an arbitrary reference.

The structural rigidity $D$ is the radius of curvature times unit bending torque and is calculated by [44]

$$D = \sum_i \frac{E_i (I_i + A_i Y_i^2)}{1 - \nu_i^2}$$  \hspace{1cm} (3.7)
where \( I \) equals the area of moment of inertia of each layer calculated about its center of area; \( Y_i = y_i - y_M \) equals each layer's vertical position measured with respect to the torque neutral axis.

### 3.2.3 Frequency of operation

For a rectangular multilayer plate, the eigenmodes in the \( x \)- and \( y \)-directions are, as a first approximation, close to those derived from beam theory [3]. For an isotropic or orthotropic rectangular plate built-in or simply supported on four edges, the frequencies (in hertz) are given approximately by [44]:

\[
f_{nj} = \frac{\pi}{2} \sqrt{\frac{G(n)^4}{L^4} + \frac{G(j)^4}{b^4} + \frac{2J(n)J(j)}{L^2b^2} \frac{Eh^3}{12m_a(1 - \nu^2)}}
\]  

(3.8)

where \( n \) is the mode number along the length; \( j \) is the mode number across width; \( L \) is the length of plates; \( b \) is the width of plates; \( G(n) = n + \frac{1}{2} \) and \( J(n) \) is \( (n + \frac{1}{2})^2 \left[ 1 - \frac{2}{\pi(n + \frac{1}{2})} \right] \) for all edges built-in; \( E \) is the Young's modulus; \( h \) is the plate thickness and \( m_a \) is the mass per unit area. For a simply supported plate, (3.8) becomes:

\[
f_{nj} = \frac{\pi}{2} \sqrt{\frac{Eh^3}{12m_a(1 - \nu^2)}} \left( \frac{n^2}{L^2} + \frac{j^2}{b^2} \right)
\]  

(3.9)

If a fluid, having a speed of sound \( v_F \), is in contact with a FPW device, and the phase velocity satisfies the inequality \( v_p < v_F \), it might be expected that the ultrasonic wave energy would not radiate away into the fluid, because the plate would act as a slow-wave propagation medium. The wave in the faster medium (the fluid) becomes evanescent, its amplitude diminishing as an inverse exponential function of the distance from the plate. FPW experiments support this simple picture for the most part, but detailed differences must be noted [2].

For a multilayered plate this approximated frequency becomes:

\[
f_{nj} = \frac{\pi}{2} \sqrt{\frac{G(n)^4}{L^4} + \frac{G(j)^4}{b^4} + \frac{2J(n)J(j)}{L^2b^2} \frac{D}{b m_a}}
\]  

(3.10)

where \( D \) is \( \frac{E L}{1 - \nu^2} \) for single layer plates and for multilayer plates is given by equation 3.7 [44].

### 3.2.4 Operation in contact with a liquid

When a semi-infinite fluid contacts the FPW device, new modes of propagation exist that are not allowed in unloaded FPW devices. The lowest-order mode, which is useful for sensing, is similar to the Scholte wave of geophysics [36]. The phase velocity of this wave in the thin-plate case ranges from zero to the velocity of sound in the fluid for plates that are thick compared to the wavelength. If the fluid is inviscid, this wave is lossless [2]. It appears that this mode is the one that is responsible for most reported flexural wave sensing results. In addition,
there is a fluid loaded asymmetric Lamb wave that can have a large attenuation factor, even for frequencies well below the speed of sound in the fluid.

It has been shown [46][10] that when a semi-infinite body of fluid contacts one side of a thin FPW device, the mass loading that the fluid produces can be described by simply adding an additional term to the mass per unit area, \( m_a \), in the phase velocity [2]:

\[
v_p = \left( \frac{B}{m_a + \rho_L \delta_E} \right)^{\frac{1}{2}}
\]  

(3.11)

where \( B \) is the bending stiffness (equation 3.3); \( m_a \) is the mass per unit area; \( \rho_L \) is the density of the fluid and \( \delta_E \) is the evanescent decay length, given by:

\[
\delta_E = \left( \frac{\lambda}{2\pi} \right) \left[ 1 - \left( \frac{v_p}{v_F} \right)^2 \right]^{-1/2}
\]  

(3.12)

This decay length \( \delta_E \) can be approximated for small \( \frac{v_p}{v_F} \) by:

\[
\delta_E \approx \left( \frac{\lambda}{2\pi} \right)
\]  

(3.13)

### 3.2.5 Sensitivity

The ability of the FPW sensor to measure small changes in mass is given by the sensitivity of the device.

\[
S_m = \frac{1}{\Delta m} \frac{\Delta f}{f} 
\]  

(3.14)

Its value for a mass per area change on the plate is (in air) [2]:

\[
S_A = -\frac{1}{2m_a}
\]  

(3.15)

In a liquid environment this becomes [2]:

\[
S_L = -\frac{1}{2(m_a + \rho_L \delta_E)}
\]  

(3.16)

This can be interpreted as an extra plate-layer of liquid with thickness \( \delta_E \) and density \( \rho_L \). The minimum detected mass density in air can be deduced from equation 3.14 and 3.15 as [16]:

\[
\Delta m = \frac{-\rho \lambda^2}{2\alpha} (3\Delta f)
\]  

(3.17)

The factor 3 is added because in practice the frequency shift must exceed the noise frequency by a factor of 3 to be significant. The minimum detected mass density in a liquid environment (deduced from equation 3.14 and 3.16) [16]:

\[
\Delta m_L = \Delta m + \frac{\delta_E}{d} \left[ \frac{-\rho_L \lambda^2}{2\alpha} (3\Delta f) \right]
\]  

(3.18)
where $\alpha$ is a material constant given by:

$$\alpha = \frac{\pi}{4} \sqrt{\frac{E}{3\rho (1 - \nu^2)}}$$  \hspace{1cm} (3.19)

To optimize the sensitivity of this device, and therefore to obtain the smallest detectable mass change, it is clear that the plate’s mass per area and the decay length (evanescent wave) need to be as small as possible. This implies that the layers in the design should be chosen as thin as possible. From equation 3.18 it can also be seen that the sensitivity is optimized when the materials constant $\alpha$ is high.

The equations in this section imply that a high sensitivity, for a FPW device operating in a liquid environment, can be obtained when:
- the material’s Young’s modulus ($E$) is as high as possible
- low Poisson’s ratio ($\nu$) and low density ($\rho$) materials are used
- the wavelength ($\lambda$) is taken small in the design
- a small decay length ($\delta_E$) is pursued.

As the decay length needs to be as small as possible, again a small wavelength $\lambda$ is required. And in the same time $v_p$ must be smaller than $v_F$. This implies [16]:

$$v_F > v_p = \frac{4h\alpha}{\lambda}$$ \hspace{1cm} (3.20)

This results in the energy trapping condition for the wavelength [16]:

$$\lambda > \lambda_F = \frac{4h\alpha}{v_F}$$ \hspace{1cm} (3.21)

When $\lambda$ is taken too small, there is dispersion of the wave in the fluid. This can be seen in the schematic representation of the phase velocity in function of $\frac{d}{\lambda}$ (see Figure 3.3). The gray area represents the correct operating region for liquid sensing, where $v_F$ is the acoustic phase velocity in the present liquid.
Figure 3.3: Schematic of the phase velocity of the FPW device, $v$, in function of the layer thickness over the acoustic wavelength, $d/\lambda$. The optimal operation region is represented with a gray box. $v_F$ is the acoustic phase velocity in the surrounding fluid.
Discussion of Design and Calculations

This chapter discusses the design and the calculations needed to optimize the FPW device operation. In the first section materials are chosen depending on the properties for device operation. Afterwards real design parameters as length, width and wavelength are discussed based on simulations that were made using MATLAB®.

4.1 Design

The modeling presented in the previous chapter (Chapter 3) is used to simulate the operation parameters for our FPW design. To investigate the operation parameters, the modeling equations are programmed into MATLAB®, the code is included in Appendix A. The design parameters are discussed in the last section of Chapter 3: section 3.2.5. Our main concern goes to:

- Layer thicknesses: $d \ll$
- Young's modulus: $E \gg$
- Poisson's ratio: $\nu \ll$
- Density: $\rho \ll$
- Wavelength: $40 \mu m \leq \lambda <$
- Plate length: $l$
- Plate width: $b$
where lambda is defined in the design by the plate length $l$ and the mode number $n$, given by the following equation:

$$\lambda = \frac{2l}{n} \quad (4.1)$$

This leads to the use of nanocrystalline diamond (NCD) as the waveguide layer, for its high Young's modulus $E$. Aluminum nitride (AlN) is chosen as the piezoelectric layer because of its high $E$-value and its low density $\rho$. However platina (Pt) has a large disadvantage in the density $\rho$ and only a small advantage in the higher Young's modulus $E$ in comparison with aluminum (Al) it is chosen for the contacting metal layers, because of its benefit in processing. Comparison of Al versus Pt is made in Chapter 9. The design parameters that are still left are:

- plate length $l$
- plate width $b$
- wavelength $\lambda$ (defined by mode number $n$ for a fixed $l$)
- layer thickness $d$

The theory of Lamb waves assumes the plate's length and width to be infinite. This can of course not be realized. Different combinations of $l$ and $b$ are simulated. In particular the influence of $b$ is illustrated in Figure 4.1. From this figure it is clear that, for a realistic $b$-value (not extremely small), the plate's width has no major influence on the device's operating frequency. For this reason the design parameter $b$ is chosen to be:

- $\frac{b}{l} = 0.2$
- $\frac{b}{l} = 0.5$
- $\frac{b}{l} = 1$

for each chosen length $l$. As plate length, different testing values are chosen: 500, 1000, 2000, 4000, 8000 $\mu$m. The mode number is varied between: 20 and 150, leading to a wavelength between 6 and 800 $\mu$m. All values are shown in Table 4.1. In the design $\lambda$ is taken only larger than 40 $\mu$m, for dispersion reasons as explained in section 3.2.5. This leaves us with 51 different combinations of the parameters $l$, $b/l$ and $n$; they are shown in Table 4.3 and 4.4. Plate's area, width, wavelength and finger spacing can easily be derived for each device, results are shown in Appendix B. In the next section the most interesting operation parameters are calculated, for all combinations with $\lambda \geq 40$: 
Figure 4.1: Illustration of the influence of $b$ for one particular example of device: $n = 150$, $l = 8000 \mu m$, $d_{NCD} = 1 \mu m$. Other devices are similar. (This example contains a plate of 4 layers: $NCD$: $1 \mu m$-$Pt$: $0.2 \mu m$ - $AlN$: $0.7 \mu m$ - $Al$: $0.15 \mu m$.)

<table>
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<tr>
<th>$\frac{2l}{n}$</th>
<th>$n = 20$</th>
<th>$n = 50$</th>
<th>$n = 80$</th>
<th>$n = 100$</th>
<th>$n = 150$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l = 500$</td>
<td>50</td>
<td>20</td>
<td>12.5</td>
<td>10</td>
<td>6.67</td>
</tr>
<tr>
<td>$l = 1000$</td>
<td>100</td>
<td>40</td>
<td>25</td>
<td>20</td>
<td>13.33</td>
</tr>
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<td>$l = 2000$</td>
<td>200</td>
<td>80</td>
<td>50</td>
<td>40</td>
<td>26.67</td>
</tr>
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<td>$l = 4000$</td>
<td>400</td>
<td>160</td>
<td>100</td>
<td>80</td>
<td>53.33</td>
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<tr>
<td>$l = 8000$</td>
<td>800</td>
<td>320</td>
<td>200</td>
<td>160</td>
<td>106.67</td>
</tr>
</tbody>
</table>

Table 4.1: Values for the wavelength $\lambda$ [$\mu m$] with chosen plate length $l$ [$\mu m$] and mode number $n$.

- Phase velocity: $v_p$
- Operation frequency: $f_{n_j}$
- Sensitivity in air: $S_A$
- Sensitivity in liquid: $S_L$
4.2 Calculations

Phase velocity, operating frequency, Sensitivity in air and in liquid environment are simulated and results are shown in Table 4.3 and 4.4 [MATLAB®] for the configuration shown in Table 4.2:

<table>
<thead>
<tr>
<th>Layer</th>
<th>material</th>
<th>$E$ [GPa]</th>
<th>$\nu$</th>
<th>$\rho$ [kg/m$^3$]</th>
<th>thickness [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waveguide</td>
<td>NCD</td>
<td>1100</td>
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<tr>
<td>Ground</td>
<td>Pt</td>
<td>170</td>
<td>0.39</td>
<td>21090</td>
<td>0.2</td>
</tr>
<tr>
<td>Piezoelectric</td>
<td>AlN</td>
<td>340</td>
<td>0.24</td>
<td>3300</td>
<td>0.7</td>
</tr>
<tr>
<td>Top metal</td>
<td>Pt</td>
<td>170</td>
<td>0.39</td>
<td>21090</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Table 4.2: Layers and properties [34][35][54].

4.2.1 Sensitivity

The sensitivity (refer to section 3.2.5), both in air and in liquid is calculated for each device. In order to simulate the change of molecules on the plate’s surface, the waveguide-layer thickness is varied. This can be assumed similar to a mass change on the plate’s surface. Results are shown in Figure 4.2 for the same device properties.

It can be seen that the sensitivity is higher for devices with smaller wavelength. However for the devices with the smallest wavelength (e.g. devices 8 and 20 as labelled in Table B.1) a severe drop in sensitivity is noticed at higher $d_{NCD}$ (plate mass). For the more medium devices (e.g. devices 26 and 47) it is noticed that the sensitivity is fairly independent on the diamond thickness $d_{NCD}$, which is an interesting feature! If the sensitivity curve is quasi-independent on $d_{NCD}$, the dependence of the frequency on $d_{NCD}$ is quasi-linear (equation 3.14). Therefore the dependence of the phase velocity on $d_{NCD}$ is quasi-linear (equation 3.1). Figure 4.3 then shows that the device is operating in the wanted region (for small $d/\lambda$).
### Table 4.3: All combinations of l, b/l and n; with device nr and ID. Simulations of phase velocity, operating frequency, Sensitivity in air and in liquid environment for all devices for $dN_{CD} = 1\, \mu m$ and layer properties as shown in Table 4.2. (Part 1 of 3)

<table>
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<td>1000</td>
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<td>793.4464</td>
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<td>396.7232</td>
<td>400.967</td>
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<td>1.59E+07</td>
<td>1.60E+07</td>
<td>3.97E+06</td>
<td>3.97E+06</td>
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<td>$</td>
<td>S_A</td>
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<td>144.2855</td>
<td>144.2855</td>
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<tr>
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<tr>
<td>$</td>
<td>S_A</td>
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<td>144.2855</td>
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<td>1.53E+07</td>
<td>1.53E+07</td>
</tr>
<tr>
<td>$</td>
<td>S_A</td>
<td>(m^2/kg)$</td>
<td>144.2855</td>
<td>144.2855</td>
<td>144.2855</td>
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<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>l (µm)</td>
<td>2000</td>
<td>2000</td>
<td>2000</td>
<td>4000</td>
<td>4000</td>
<td>4000</td>
</tr>
<tr>
<td>n</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>b/l</td>
<td>1</td>
<td>0.5</td>
<td>0.2</td>
<td>1</td>
<td>0.5</td>
<td>0.2</td>
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<tr>
<td>$vp$ (m/s)</td>
<td>952.8933</td>
<td>952.8961</td>
<td>952.9274</td>
<td>99.1306</td>
<td>99.1808</td>
<td>100.2418</td>
</tr>
<tr>
<td>$fnj$ (Hz)</td>
<td>2.38E+07</td>
<td>2.38E+07</td>
<td>2.38E+07</td>
<td>2.48E+05</td>
<td>2.48E+05</td>
<td>2.51E+05</td>
</tr>
<tr>
<td>$</td>
<td>S_A</td>
<td>(m^2/kg)$</td>
<td>144.2855</td>
<td>144.2855</td>
<td>144.2855</td>
<td>144.2855</td>
</tr>
<tr>
<td>$</td>
<td>S_L</td>
<td>(m^2/kg)$</td>
<td>27.662</td>
<td>27.662</td>
<td>27.6617</td>
<td>6.7904</td>
</tr>
</tbody>
</table>
Table 4.4: All combinations of l, b/l and n; with device nr and ID. Simulations of phase velocity, operating frequency, Sensitivity in air and in liquid environment for all devices for \( d_{NCD} = 1 \) µm and layer properties as shown in Table 4.2. (Part 2 of 3)
Table 4.5: All combinations of \( l, b/l \) and \( n \); with device nr and ID. Simulations of phase velocity, operating frequency, Sensitivity in air and in liquid environment for all devices for \( d_{NCD} = 1 \, \mu m \) and layer properties as shown in Table 4.2. (Part 3 of 3)
Discussion of Design and Calculations

Figure 4.2: a) Sensitivity in air: $d_{NCD}$ dependent, b) Sensitivity in liquid environment: quasi $d_{NCD}$ independent. Devices 2, 5,..., 50 as labelled in table 4.3, 4.4 and 4.5 are shown (these have $b = l/2$). Higher sensitivity in liquid is noticed for devices with smallest wavelength (e.g. 8 and 20), and sensitivity is going down for devices with rising wavelength.
4.2 Calculations

Figure 4.3: Dependence on $d_{NCD}$ for $S_L$, $f$ and $v_p$. If the dependence of the sensitivity on waveguide layer thickness is quasi-independent, the device is, for small $d/\lambda$, operating in the correct region.
Materials influence

Investigations have been made to analyze the influence of the material on the device operation. A first example was already given in section 4.2.1 using theoretically useful values of the different layer thicknesses. The sensitivity was calculated for a diamond-FPW device (Figure 4.2 comparing air to liquid environment).

Simulation 1: This analysis simulates the operating frequency and sensitivity for a diamond-waveguide layer as it is processed. Layer thicknesses are shown in Table 4.6. Results are shown in Figure 4.4.

Simulation 2: In this case the NC-diamond is substituted by a SiO₂ layer with the same layer thickness, in order to compare the device operation. From Figure 4.4 compared to Figure 4.5 it is clear that for reasons of sensitivity the NCD is a better material for the FPW sensor than the more common SiO₂. Also comparison of the sensitivity in air is made and shown in Figure 4.8. NCD clearly shows better detection of small mass changes at the plate.

Simulation 3: Comparison is made for when the Pt ground and top metal are changed into Al (Figure 4.6). It is seen that there is a small drop in sensitivity for the case of Pt, and that Al has better properties, but Pt has the benefit that its processing is easier.

Simulation 4: Finally comparison is made between operation with AlN and PZT as piezoelectric layer. Figure 4.7 shows the same device with a piezoelectric layer of PZT (Lead Zirconate Titanate) instead of the previously used AlN layer. This calculation was made for reasons of possible AlN deficiency at the start of the processing. AlN has better properties for FPW sensitivity and at the same time it is easier in processing, and in the control of stress in the layer.

From these simulations it can be concluded that NCD is a promising material for the use in FPW sensors. Mainly for its material properties in the sensitivity of the device, but also for its excellent bio-compatibility¹.

Other calculations made by Francis L. investigated the minimum detected mass density in gas and in fluid for a simple FPW device comparing NCD to SiO₂. Most likely values are taken for thickness: 1 µm, a wavelength of 100 µm and a noise frequency of 1 Hz. Results are shown in Table 4.8. It is clear that the minimum detected mass density is a lot lower for the plate-material with the highest α both for detection in gas and in a liquid environment. Comparing the

¹Diamond has been touted as the biomaterial of the 21st century, and many uses for diamond surfaces in biomedical applications have been proposed including coatings for artificial heart valves, prosthetic devices, joint replacements, catheters and stents, orthopedic pins, the roots of false teeth, dental instrument tips, surgical scalpels and microtome blades, and even the complete fabrication of artificial heart valves. Diamond electrodes also are widely employed in biosensors [Nanomedicine, Volume IIA: Biocompatibility by Robert A. Freitas Jr.].
4.2 Calculations

<table>
<thead>
<tr>
<th>Thickness (µm)</th>
<th>NCD</th>
<th>SiO₂</th>
<th>Pt</th>
<th>Al</th>
<th>AlN</th>
<th>PZT</th>
<th>Pt</th>
<th>Al</th>
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</thead>
<tbody>
<tr>
<td>Simulation 1</td>
<td>1</td>
<td>0.1</td>
<td>0.8</td>
<td>0.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Simulation 2</td>
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<td>0.1</td>
<td>0.8</td>
<td>0.15</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simulation 3</td>
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<td>0.1</td>
<td>1</td>
<td>0.8</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Simulation 4</td>
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<td>0.1</td>
<td>0.8</td>
<td>0.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.6: Layer thicknesses for simulation of devices.

<table>
<thead>
<tr>
<th>Material</th>
<th>NCD</th>
<th>SiO₂</th>
<th>Pt</th>
<th>Al</th>
<th>AlN</th>
<th>PZT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s Modulus $E$ [GPa]</td>
<td>1100</td>
<td>70</td>
<td>170</td>
<td>68</td>
<td>340</td>
<td>52</td>
</tr>
<tr>
<td>Poisson’s ratio $ν$</td>
<td>0.12</td>
<td>0.17</td>
<td>0.39</td>
<td>0.34</td>
<td>0.24</td>
<td>0.29</td>
</tr>
<tr>
<td>density $ρ$ [kg/m³]</td>
<td>3500</td>
<td>2200</td>
<td>21090</td>
<td>2700</td>
<td>3300</td>
<td>7800</td>
</tr>
</tbody>
</table>

Table 4.7: Material constants used in the simulations [22; 26; 34; 35; 54].

materials constant $α$, it is highest for the NCD, resulting in its better sensitivity in comparison with SiO₂.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symb.</th>
<th>Expression</th>
<th>Units</th>
<th>SiO₂</th>
<th>NCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material density constant $ρ$</td>
<td>$ρ$</td>
<td>$\frac{π}{4} \sqrt{\frac{E}{3ρ(1-ν²)}}$</td>
<td>kg/m³</td>
<td>2200</td>
<td>3500</td>
</tr>
<tr>
<td>Phase velocity $v_p$</td>
<td>$v_p$</td>
<td>$\frac{E}{4ρ}$</td>
<td>m/s</td>
<td>104</td>
<td>347</td>
</tr>
<tr>
<td>Frequency $f_{n1}$</td>
<td>$f_{n1}$</td>
<td>$\frac{2π}{λ}$</td>
<td>MHz</td>
<td>1.04</td>
<td>3.47</td>
</tr>
<tr>
<td>Penetration depth $δ$</td>
<td>$δ$</td>
<td>$\frac{2λ}{V_p^2} \left[1 - (v_p/V_p)^2\right]^{-1/2}$</td>
<td>µm</td>
<td>16</td>
<td>16.5</td>
</tr>
<tr>
<td>Minimum detected mass density in a gas $Δm$</td>
<td>$Δm$</td>
<td>$\frac{ρx^2}{2a} (3Δf)$</td>
<td>µg/mm²</td>
<td>13</td>
<td>6</td>
</tr>
<tr>
<td>Minimum detected mass density in a fluid $Δm_F$</td>
<td>$Δm_F$</td>
<td>$Δm + \frac{a}{h} \left[\frac{ρx^2}{2a}((3Δf)^2)\right]$</td>
<td>µg/mm²</td>
<td>105</td>
<td>34</td>
</tr>
</tbody>
</table>

Table 4.8: Comparison of minimum detected mass density in gas and fluid for NCD and SiO₂ [Laurent A. Francis]. NCD is the better material for a small detection limit.
Figure 4.4: Simulation 1: Frequency and sensitivity (in liquid) for an FPW device containing following layers: NCD-Pt-AlN-Pt, thicknesses as in Table 4.6. The sensitivity shows a better detection limit for devices with small wavelength (e.g. 8 and 20). Devices 2, 5..., 50 as labelled in table 4.3, 4.4 and 4.5 are shown.
4.2 Calculations

Figure 4.5: Simulation 2: Frequency and sensitivity for an FPW device containing following layers: SiO$_2$-Pt-AlN-Pt, thicknesses as in Table 4.6. The sensitivity shows a better detection limit for devices with small wavelength (e.g. 8 and 20). In comparison with Figure 4.4 NCD has the better properties for a low mass detection limit.
Discussion of Design and Calculations

Figure 4.6: Simulation 3: Frequency and sensitivity for an FPW device containing following layers: NCD-Al-AlN-Al, thicknesses as in Table 4.6. In comparison with Figure 4.4 Al has a small advantage for a low mass detection limit, but Pt is still considered as metal layer for its easier processing.
Figure 4.7: Simulation 4: Frequency and sensitivity for an FPW device containing following layers: NCD-Pt-PZT-Pt, thicknesses as in Table 4.6. In comparison with Figure 4.4 AlN has is better for a low mass detection limit, this simulation was made for the case of a deficiency in AlN.
Figure 4.8: Comparison of Sensitivity for NCD and SiO$_2$ for air environment, properties as in table 4.6
4.2 Calculations

4.2.2 Torque

Not only the sensitivity for NCD and SiO$_2$ was compared, also calculations were made to compare the torque for these samples. The torque per unit voltage across the piezoelectric layer is given in section 3.2.2 by equation 3.5. For a simplified 4 layer structure:
- 1 µm NCD/SiO$_2$
- 0.1 µm Pt
- 0.5 µm AlN
- 0.15/2 µm Pt (the finger structure is simplified by use of a uniform film with half the film thickness)

the neutral axis is calculated (equation 3.6), with the bottom as reference point. For the SiO$_2$ layer the neutral axis is at 1.13 µm from the reference point: in the AlN layer, as shown in Figure 4.9. However, for the NCD structure the neutral axis is at 0.63 µm from the reference point, which is in the NCD layer.

![Diagram of 4-layer structure with neutral axes](image)

Figure 4.9: Calculations of the neutral axis for NCD/SiO$_2$ simple 4-layer structure.

This has its influence on the torque for the structure: the torque per unit voltage is higher for the NCD layer compared to SiO$_2$ as shown in Figure 4.10. Or inverted: for equal force on the structure a lower voltage is needed in the case of the NCD (Figure 4.11).
Discussion of Design and Calculations

Figure 4.10: Calculations of $M_p$ for NCD/SiO$_2$ simple 4-layer structure.

Figure 4.11: Inverted $M_p$ for NCD/SiO$_2$ simple 4-layer structure.
Thin Film Microfabrication Techniques

5.1 Introduction

MEMS technology is based on a number of tools and methodologies, which are used to form small structures with dimensions in the micrometer scale. Microfabrication can be effectively applied to yield a single device or thousands of devices. There are three basic steps in MEMS technology, which are:
- depositing thin films of material on a substrate,
- applying a patterned mask on the films by photolithographic imaging,
- etching the films selectively to the mask.

A MEMS process is usually a structured sequence of these operations to form an actual device.

A MEMS device can be made by surface micromachining and/or bulk micromachining. In surface micromachining the structures are build one layer at a time on top of the substrate by use of thin films process techniques. The structural layers, which will form the actual microcomponents, are deposited on a sacrificial layer. This sacrificial layer is etched away in another process step, without affecting the structural layer. A free standing structure is formed. In bulk micromachining three dimensional structures are formed by etching in the bulk of the material. The practical work reported uses thin film process techniques. Thin films are deposited on a substrate without a sacrificial layer. These thin films are processed by several techniques to create different structures. The process and deposition techniques of thin films are discussed in depth in the following sections.

5.2 Chemical Vapor Deposition

In chemical vapor deposition, the source materials are brought by a gas phase flow into the vicinity of the substrate, where they decompose and react to deposit a film on the substrate. Gaseous by-products are pumped away, as shown schematically in Figure 5.1. The decomposition of the source gases is induced either thermally (thermal CVD) or by the use of a plasma (plasma enhanced CVD, PECVD), see section 5.2, 5.3 respectively.
5.3 Plasma Enhanced Chemical Vapor Deposition

A plasma is a fully or partially ionized gas composed of ions, electrons, neutrons and radicals [1]. A plasma is produced when an electric field of sufficient magnitude is applied to a gas, causing the gas to break down and become ionized. The plasma is initiated by free electrons that are released by some means such as field emission from a negatively biased electrode. The free electrons gain kinetic energy from the electric field. In the course of their travel through the gas, the electrons collide with gas molecules and lose their energy. The energy transferred in the collisions causes the gas molecules to be ionized (i.e., convert to free electrons and ions). The freed electrons gain kinetic energy from the field, and the process continues. Therefore, when the applied voltage is larger than the breakdown potential, a sustained plasma is formed. An ionized gas generated using high electric fields is known as a cold plasma or electrical discharge. Electrical discharge is the most practical means of creating and sustaining a low temperature plasma in the laboratory.

Many methods of coupling electrical energy into gases to generate a plasma have been developed using both d.c. as well as a.c. power sources. The two most common methods for coupling electrical energy into a gas discharge are through capacitive coupling (CCP) (Figure 5.2 a), or through induction as is done with an inductively coupled plasma (ICP) (Figure 5.2 b) [1]. Inherently different plasma conditions are created with CCP and ICP discharges and the choice of ICP or CCP discharge depends on the application.

Capacitively coupled plasmas are characterized by a relatively low plasma density but a high energy ion bombardment of the substrate surface. Most of the chemistry occurs on the substrate surface within the reactor due to the high energy ion bombardment. High energy ions causes relatively unselective fragmentation of the surface adsorbed species. Deposition or etch processes occur depending on the power and the involved molecules. These plasmas are typically used for thin film deposition/modification. In addition, due to the high energy uni-directional ions, these plasmas are also useful for high aspect ratio anisotropic etching.

Remote plasma processes (such as ICP) differ from CCP in that they produce higher density plasmas and the source gases are injected downstream of
5.4 Physical Vapor Deposition (PVD)

PVD [18] covers a number of deposition technologies in which material is released from a source and transferred to the substrate without a chemical reaction. The two most important technologies are evaporation and sputtering.

5.4.1 Evaporation

In evaporation the substrate is placed inside a vacuum chamber, in which a piece (source) of the material to be deposited is also located. The source material is then heated to the point where it starts to boil and evaporate. A vacuum is required to allow the molecules to evaporate freely in the chamber. They subsequently condense on all surfaces. This principle is the same for all

\[ 1 \text{eV} = \frac{e}{k_B} = 11604 \text{K}, \]  
\( e \) is the electron charge and \( k_B \) the Boltzmann constant.
evaporation technologies, only the method used to heat (evaporate) the source material differs.

There are two popular evaporation technologies, namely e-beam evaporation and resistive evaporation in which the name refers to the heating method. In e-beam evaporation, an electron beam is aimed at the source material causing local heating and evaporation. In resistive evaporation a tungsten boat, containing the source material, is heated electrically with a high current to make the material evaporate. Many materials are restrictive in terms of what evaporation method can be used, which typically relates to the phase transition properties (the temperature at which the material starts to evaporate) of that material. A schematic diagram of a typical e-beam evaporation system is shown in Figure 5.3.

![Figure 5.3: Typical system for e-beam evaporation of materials. The e-beam evaporates the source material which condenses on the wafer [31].](image)

5.4.2 Sputtering

Sputtering is a technology in which the material is released from the source at a much lower temperature than in the evaporation method. The substrate is placed in a vacuum chamber with the source material, named a target, and an inert gas is introduced at low pressure. A gas plasma is formed using an RF or DC power source, causing the gas to become ionized. The ions are accelerated towards the surface of the target, causing atoms of the source material to break off from the target in vapor form and condens on all surfaces including the substrate. As for evaporation, the basic principle of sputtering is the same for all sputtering technologies. The differences typically relate to the manner in
which the ion bombardment of the target is realized. A schematic diagram of
a typical RF sputtering system is shown in Figure 5.4.

![Schematic diagram of a typical RF sputtering system](image)

Figure 5.4: Typical RF sputtering system. Loose particles due to ion bombard-
ment of the target condens on the wafer [31].

### 5.5 Photolithography

Photolithography is the standard process to transfer a pattern, which has been
designed with a computer assisted program (e.g. CleWin), onto a certain mate-
rial. The process sequence is illustrated in Figure 5.5. A mask with the desired
pattern is created. The mask is a glass plate with a patterned chromium layer
on the surface. Electron-beam lithography is used to write the mask pattern
from the designed data. In the photolithographic process, a photoresist layer
(photostructurable polymer) is spin-coated onto the material to be patterned.
Next the photoresist layer is exposed to UV light through the mask. This step
is done in a mask aligner, in which mask and wafer are aligned before the sub-
sequent exposure step is performed. The mask is brought in contact with the
substrate and the image of the mask is projected onto the photoresist-coated
substrate. The exposed or the unexposed photoresist areas are removed during
the resist development process, depending on wether positive or negative pho-
toresist was used. The remaining photoresist acts as a protective mask during
the etching process, which transfers the pattern onto the underlying material.
The remaining photoresist is removed after etching, and the next layer can be
deposited and patterned. A more detailed explanation of optical lithography
and lithographic patterns can be found in “Semiconductor devices: Physics and
Technology” (Sze S. M., 1958) [37].

A related pattern transfer process is the lift-off technique, shown in Fig-
ure 5.6, used to structure a thin-film material which would be difficult to etch.
First, a resist pattern is formed on the substrate, as shown in Figure 5.6 a
Figure 5.5: Schematic of a photolithographic process sequence for structuring a thin-film layer [20].

and 5.6 b. The film is then deposited over the resist and the substrate, illustrated in Figure 5.6 c. The film thickness must be smaller than that of the resist in order to avoid a continuous film. By removing the underneath photoresist, the thin-film material on top is also removed by “lifting it off,” leaving a structured thin film on the substrate (Figure 5.6 d). High resolution can be obtained using the lift-off technique. However, it is not as widely applicable for very-large-scale integration, where dry etching is the preferred technique.

5.6 Etching

Etching is mostly divided into two classes, wet etching using liquid chemicals and dry etching using gas-phase chemistry. Both methods can be either isotropic, i.e., provide the same etch rate in all directions, or anisotropic, i.e., provide different etch rates in different directions (see Figure 5.7). The criteria for selecting a particular etching process encompass the material etch rate, the selectivity to the material to be etched versus other materials, and the isotropy/anisotropy of the etching process. An overview of various etching chemistries used in microfabrication can be found in [51].
5.6 Etching

5.6.1 Wet chemical etching

Wet chemical etching [19] is used extensively in semiconductor processing. Starting from the sawed semiconductor wafers, chemical etchants are used for lapping and polishing to give an optically flat, damage-free surface. Prior to thermal oxidation or epitaxial growth, the semiconductor wafers are chemically cleaned and scrubbed to remove contamination that results from handling and storing. For many discrete devices and integrated circuits of relatively large dimensions ($\gtrsim 3 \ \mu m$), chemical etching is used to make patterns and to open windows in insulating materials. The mechanisms for wet chemical etching involve three essential steps:

Figure 5.6: Lift-off process for pattern transfer.

Figure 5.7: Difference between anisotropic and isotropic etching [31].
• the reactants are transported (e.g., by diffusion) to the reacting surface,

• chemical reactions occur at the surface,

• the products from the surface are transported away (e.g., by diffusion).

Both agitation and the temperature of the etchant solution will influence the etch rate. In IC processing, most wet chemical etchings proceed by dissolution of a material in a solvent or by conversion of a material into a soluble compound which subsequently dissolves in the etching medium.

5.6.2 Dry etching

In pattern transfer operations, a resist pattern is defined by an optical lithographic process to serve as a mask for etching of its underlying layer (see section 5.5). Most of the layer materials are amorphous or polycrystalline thin films. If they are etched in a wet chemical etchant, the etch rate is generally isotropic (illustrated in Figure 5.7 a).

The major disadvantage of wet chemical etching for pattern transfer is the undercutting of the layer underneath the mask, resulting in a loss of resolution in the etched pattern. In practice, for isotropic etching the film thickness should be about one third or less of the resolution required. If patterns are required with resolutions much smaller than the film thickness, anisotropic etching must be used. To achieve anisotropic etching, dry etching methods have been developed [33].

The dry etching technology can be split in three separate classes called reactive ion etching (RIE), sputter etching, and vapor phase etching. In RIE, the substrate is placed inside a reactor in which several gases are introduced. A plasma is formed in the gas mixture using an RF power source, breaking the gas molecules into ions. The ions are accelerated towards the surface of the material being etched. There they react and form another gaseous material. This is known as the chemical part of reactive ion etching. There is also a physical part which is similar to the sputtering deposition process (see section 5.4.2). If the energy of the ions is high enough, they can knock atoms out of the material to be etched without a chemical reaction. It is a very complex task to develop dry etch processes that balance chemical and physical etching, since there are many parameters to adjust. By changing the balance it is possible to influence the anisotropy of the etching, since the chemical part is isotropic and the physical part highly anisotropic. The combination can form sidewalls that have shapes from rounded to vertical. A schematic of a typical reactive ion etching system is shown in Figure 5.8.

A special subclass of RIE is deep RIE (DRIE). In this process, etch depths of hundreds of microns can be achieved with almost vertical sidewalls. The primary technology is based on the so-called "Bosch process" [18], named after the German company Bosch which filed the original patent. Two different gas
compositions are alternated in the reactor. The first gas composition creates a polymer on the surface of the substrate, and the second gas composition etches the substrate. The polymer is immediately sputtered away by the physical part of the etching but only on the horizontal surfaces and not at the sidewalls. Since the polymer only dissolves very slowly in the chemical part of the etching, it builds up on the sidewalls and protects them from etching. The process can easily be used to etch completely through a silicon substrate (e.g., bulk micromachining), and etch rates are 3-4 times higher than for wet etching.

Figure 5.8: Typical parallel-plate reactive ion etching system [31].
Design and Process Flow

This chapter describes the design of the FPW devices. As seen in the last chapter a mask is needed for microfabrication of devices like the FPW sensor. This mask is presented here, together with the process flow for the actual device processing.

6.1 Design

The device consists of 5 layers:

1. **Substrate**: as support for the FPW membrane layers and handling (e.g. Silicon).

2. **Waveguide layer**: a layer with the better material for the propagation of the waves (e.g. NCD).

3. **Ground layer**: an electrical ground for the transducers electrical signals (e.g. Pt).

4. **Piezoelectric layer**: for actuation and detection of the waves in the plate (e.g. AlN).

5. **Top metal layer**: in the form of an ITD structure for electrical actuation and detection of the waves (e.g. Pt).

As a substrate an ordinary silicon wafer is used. This layer is used for handling purposes (a thin film can not exist on its own), and can easily be used in standard techniques for microfabrication. Then a waveguide layer is deposited on top. This layer has the better properties for good sensitivity and FPW operation. These properties are best employed when the plate’s neutral axis (section 3.2.2) is in this layer. The next layer is the ground layer to ground the electrical signals for excitation and detection of the acoustic waves. On top of this the piezoelectric layer is deposited, in order to launch the acoustic waves in the plate, by applying a voltage on the top metal in the form of IDT’s.

A topview and a cross-sectional view are shown in Figure 6.1. A conventional rectangular shape is shown in Figure 6.1 a), and a rounded structure is shown in Figure 6.1 b). The round\(^1\) structure was considered for reasons of stress.

\(^1\)Frequencies of the round structures are calculated for simple 1-layer diamond devices in Appendix C.
Stress in the thin layers results into a buckling of the membrane, therefore the stress is concentrated in the 4 corners, and the device fragility is enhanced. To cope with this problem a round structure was proposed. No earlier experiments about this are found in literature. The round device can not be excited with an IDT-comb structure as the conventional rectangular one, instead a full ring shaped transducer is used (Figure 6.1 b).

![Rectangular vs Round](image)

**Figure 6.1:** Schematic view of a general FPW device layout. Top and cross-sectional view, for a conventional rectangular and a round device.

For our process 4 inch wafers are used. The wafer contains 67 devices, including 63 different designs and 4 copies. Some of the outer devices will probably be lost due to wafer handling. There are 3 different device sizes:

- $15 \times 1.4 \text{ cm}^2$
- $16 \times 1 \text{ cm}^2$
- $36 \times 0.7 \text{ cm}^2$

The full layout of the wafer is shown in Figure 6.2, where each device is represented by its ID. As suggested in section 5.5 the fabrication of micromachined devices needs the design of a mask for lithography. The mask-design of the FPW device is done in “CleWin”. In total 3 mask are needed:

1. for opening a contact to the ground layer: contact pad mask
2. for the top metal structure of the IDT’s: metal mask
3. for the etching of the membrane through the full silicon substrate: membrane mask
6.1 Design

Figure 6.2: Layout of the different devices on the mask (for 4 inch wafer).

an example for one particular device (N320.42) is shown in Figure 6.3.
Figure 6.3: Mask-design example for one particular device (N320.42). a) The contact pad mask for opening a contact to the electrical ground layer. b) The top metal mask which contains the IDT structures for electrical actuation and detection of the wave. c) The membrane mask for a back-side etch of the substrate in order to obtain a membrane. d) The total stack of the previous layers.
6.2 Process Flow

The general process steps are shown in Figure 6.4 and 6.5. All practical steps are explained and illustrated in section 8.1, including encountered problems and issues.

Starting point is a conventional silicon wafer, which is cleaned to remove all unwanted particles.

Step 1: The wafer is sent out to the rho-BeSt company (Austria) who will coat it with a NCD layer.

Step 2: The ground layer can be deposited on the NCD after additional cleaning.

Step 3: With conventional microprocessing techniques (as discussed in Chapter 5) special resist for lift-off is spun.

Step 4: This resist is soft-baked and patterned by exposure with UV light in contact with the contact pad mask. After development in the proper chemicals the exposed parts of the resist are removed.

Step 5: The next step is to sputter the piezoelectric layer on top.

Step 6: A lift-off process is performed to open the contact pads to the ground layer.

Step 7: For the second time resist is spun. Exposure is this time in contact with the metal mask.

Step 8: After development of the resist, the top metal layer is deposited.

Step 9: Lift-off of the top metal, to obtain the IDT-comb structure.

Step 10: Al is deposited on the backside as hard etching mask.

Step 11: Wet-etching after lithography with the membrane mask.

Step 12: Finally dry etching (Bosh process) will etch trough the whole wafer, to be left with the FPW membrane.
Start with Silicon substrate
With full diamond layer on top

Deposition of Pt layer

Spinning of resist for lift-off

Patterning of the resist with lithography

Deposition of AlN piezoelectric layer

Lift-off

Spinning of resist for lift-off

Figure 6.4: Overview of the general process steps for a FPW device (part 1).
6.2 Process Flow

Figure 6.5: Overview of the general process steps for a FPW device (part 2).
Piezoelectric characterization of AlN

The material used as piezoelectric layer is aluminum nitride (AlN). This material can be deposited on a wafer through sputtering (Section 5.4.2). A problem encountered is that there was no information available on the piezoelectric properties of the AlN-target in the sputtering equipment. The piezoelectric coefficient $d_{31}$ (piezoelectric coupling coefficient) needs to be determined for the FPW's piezoelectric transducer. An experiment was set up to obtain this value. A micromachined cantilever was designed for its piezoelectric respons.

This cantilever design needs multiple layers: the substrate, a ground electrode, the piezoelectric layer and a top electrode. A cross-section is presented in Figure 7.1. When a voltage is applied between the top and the ground electrode, the piezoelectric material will force the beam to deflect. The deflection $\delta$ is a measure for the piezoelectric constant $d_{31}$.

![Schematic cross-section of a cantilever beam for AlN characterization.](image)

**Figure 7.1:** Schematic cross-section of a cantilever beam for AlN characterization.

### 7.1 Model

For a cantilever beam with length $L$ and width $b$, and different layers with thickness $h_i$, the total tip deflection $\delta$ [\(\mu\text{m}\)] with an applied voltage $V$ [\(\text{V}\)] is [30][14][43]:

$$\delta = \frac{M_p L^2}{EI} \frac{1}{2}$$

(7.1)
where $M_p$ [Nm] is the bending moment given by:

$$M_p(x) = \frac{bd_{31}}{h_p} \int_0^L E_p (z - z_0) \, dz$$  \hspace{1cm} (7.2)

The contact force at the tip $F_c$ [N] is

$$F_c = \frac{3M_p}{2L} - \frac{3d_{31}EI}{L^3}$$  \hspace{1cm} (7.3)

with the effective section modulus [Pam$^4$]

$$\bar{EI} = \frac{A_x D_x - B_x^2}{A_x}$$  \hspace{1cm} (7.4)

and the location of the neutral axis:

$$z_0 = \frac{B_x}{A_x}$$  \hspace{1cm} (7.5)

$A_x$, $B_x$ and $D_x$ are given by:

$$A_x = \int \int_A E(z) \, dA$$  \hspace{1cm} (7.6)

$$B_x = \int \int_A E(z) z \, dB$$  \hspace{1cm} (7.7)

$$D_x = \int \int_A E(z) z^2 \, dA$$  \hspace{1cm} (7.8)

The interesting piezoelectric coefficient is $d_{31}$ [C/N] and can be determined by applying a known voltage to a cantilever beam with known properties (length, width, layer thicknesses, Young's modulus). An example is given in Table 7.1. This example shows that for this beam, when a voltage of 10 V is applied, the tip deflection will be 48.38 $\mu$m for a given piezoelectric constant. This example can be reversed: the piezoelectric constant can be determined if the tip-deflection is measured for a known applied voltage.
### 7.1 Model

<table>
<thead>
<tr>
<th>Parameters cantilever beam:</th>
<th>Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length L (µm)</td>
<td>29000</td>
</tr>
<tr>
<td>Width b (µm)</td>
<td>1000</td>
</tr>
<tr>
<td>Thickness layer 5 (µm)</td>
<td>80</td>
</tr>
<tr>
<td>Thickness layer 4 hp (µm)</td>
<td>5.00E-01</td>
</tr>
<tr>
<td>Thickness layer 3 (µm)</td>
<td>0.05</td>
</tr>
<tr>
<td>Thickness layer 2 (µm)</td>
<td>1</td>
</tr>
<tr>
<td>Thickness layer 1 (µm)</td>
<td>0</td>
</tr>
<tr>
<td>Total thickness h (µm)</td>
<td>81.55</td>
</tr>
<tr>
<td>h/2 (µm)</td>
<td>40.775</td>
</tr>
<tr>
<td>Initial gap d0 (µm)</td>
<td>1</td>
</tr>
<tr>
<td>Piezoelectric coefficient layer 4 d 31 (pC/N)</td>
<td>-3.125</td>
</tr>
<tr>
<td>Applied voltage (V)</td>
<td>-10</td>
</tr>
<tr>
<td>A_x</td>
<td>5835.25</td>
</tr>
<tr>
<td>B_x</td>
<td>-0.0050029</td>
</tr>
<tr>
<td>D_x</td>
<td>3.3611E-06</td>
</tr>
<tr>
<td>Effective section modulus (Pam²)</td>
<td>3.36E-06</td>
</tr>
<tr>
<td>Location of neutral axis (µm)</td>
<td>-0.8573562</td>
</tr>
<tr>
<td>Tip deflection (d max = d0) (µm)</td>
<td>-48.375152</td>
</tr>
<tr>
<td>Contact force at the tip (N)</td>
<td>0</td>
</tr>
<tr>
<td>Bending moment M_p (Nm)</td>
<td>-3.86E-07</td>
</tr>
</tbody>
</table>

Table 7.1: Example of cantilever beam deflection for an applied voltage. [Special thanks to Gerard Klaasse for this excel sheet]
Piezoelectric characterization of AlN

7.2 Design

The cantilevers where designed for a 4 inch wafer, including 4 beams with different length and width shown in Table 7.2. They contain 4 layers:

<table>
<thead>
<tr>
<th>beam 1</th>
<th>length L [µm]</th>
<th>width b[µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam 2</td>
<td>29000</td>
<td>1000</td>
</tr>
<tr>
<td>beam 3</td>
<td>22000</td>
<td>4000</td>
</tr>
<tr>
<td>beam 4</td>
<td>28000</td>
<td>3000</td>
</tr>
<tr>
<td>beam 5</td>
<td>22000</td>
<td>2000</td>
</tr>
</tbody>
</table>

Table 7.2: Length and width of the different cantilever beam designs.

1. The substrate: etched to obtain the wanted beam thickness (e.g. Si)

2. An electrical ground layer (e.g. Pt)

3. The piezoelectric layer (e.g. AlN)

4. A top metal layer (e.g. Al)

In order to obtain a cantilever, 5 masks had to be designed: Figure 7.2 shows the final mask-design for 1 device example (the total stack is shown on top and the 5 mask layers are shown below).

1. **Pt mask**: Patterning of the ground layer (Pt) by lift-off

2. **AlN mask**: Patterning of the piezoelectric AlN by wet etching

3. **Al mask**: The top metal layer (Al) needs to be patterned (wet etching)

4. **U-shape mask**: The front-side needs to be dry etched

5. **Back mask**: A back-side dry etching mask is needed to obtain the correct cantilever beam thickness

7.3 Process Flow

The processing steps for the cantilevers are quite similar to the steps in the FPW process flow. The same materials are used and therefore the process steps are similar (Figure 7.3 and 7.4). Again the detailed illustrated processing is shown in section 8.2. Main process steps are:

**Step 1**: Spinning of resist for lift-off of Pt
Step 2: Exposure with Pt-mask and development

Step 3: Deposition of Pt layer

Step 4: Lift-off

Step 5: Deposition of AlN layer

Step 6: Spin resist for AlN etch

Step 7: Exposure with AlN-mask and development

Step 8: Etching of AlN

Figure 7.2: Mask design for cantilevers.
Step 9: Deposition of Al layer

Step 10: Spin resist for Al etch

Step 11: Exposure and development with Al-mask

Step 12: Etching of Al

Step 13: Deposition of resist

Step 14: Exposure with U-shape mask and development

Step 15: Front DRIE etch

Step 16: Deposition of resist on the back-side

Step 17: Exposure with back mask and development

Step 18: Back DRIE etch to be left with cantilever shaped structures
7.3 Process Flow

Figure 7.3: Schematic representation of the process flow for cantilevers. (Part 1 of 2)
Piezoelectric characterization of AlN

Figure 7.4: Schematic representation of the process flow for cantilevers. (Part 2 of 2)
This chapter illustrates the most processing steps. Starting with the description of errors in the first process flow, followed by the adjustments made to solve these problems.

### 8.1 FPW biosensors

To obtain processing skills and test the theoretical process flow described in section 6.2, silicon wafers, with a 1 \( \mu \text{m} \) thick layer of SiO\(_2\) on both sides, are processed. Processing steps described in this section are similar for NCD, some steps are slightly adjusted.

First the wafers are cleaned in a chemical solution called “Piraña” (1 dose H\(_2\)O\(_2\) and 4 doses H\(_2\)SO\(_4\)) to remove all organic contaminants. After dehydration, the first layer is deposited: a thin layer of Pt as ground layer. Then resist for lift-off is spun and exposed with the contact pad mask. After development there are squares of resist at the unexposed parts of the wafer: Figure 8.1. The wafer is then ready for deposition of AlN: Figure 8.2. It can be seen that the thin layer of AlN on the resist is not continuous. This is not a problem since this part will be removed in the lift-off process (section 5.5). It is even caused by the resist that is underneath. After the lift-off procedure (~30 minutes in an ultrasonic acetone bath) the rest of the resist needs to be removed, therefore

---

**Figure 8.1:** SiO\(_2\) wafer with lift-off resist developed with contact pad mask.
the wafers are plunged for a couple of minutes in “OPD262”. Hereby the AlN is attacked and peeled off of the wafer (see Figure 8.4). This problem can be solved by removing the resist in “Microstrip”.

The next step is the deposition of the top metal layer. Again resist is spun for lift-off and this time it is exposed with the metal mask (Figure 8.5). It can be
seen that there are several flaws in the picture. Some are due to dust particles on the lens of the camera used to make these pictures, others are scratches and dust particles. The 2 latter should be avoided as much as possible. Afterwards the top metal is deposited and lifted-off (Figure 8.6).

For alignment of 2 layers (e.g. contact pad pattern in the AlN and the metal pattern in the Pt), alignment crosses are needed. An example of an alignment-box (mostly on the first deposited patterned layer) with crosses is shown in Figure 8.7. In order to align all layers of the device, each layer has its own number to fit in the alignment-box (see also section 5.5). Figure 8.8 shows this box after the top metal lift-off. The contact pad mask contains crosses number 3, the metal mask contains the whole alignment-box with crosses number 2, the back contains another alignment-box with crosses number 2 (as shown in Figure 8.9).

For the back-side of the Si/SiO₂ wafers the SiO₂ can also be used as an etching mask in dry etching, together with resist. To pattern the SiO₂ a layer of resist is spun and developed in a "351" chemical solution. Again the AlN layer delaminated completely from the front-side in this development. This can be prevented by protecting the front-side with a full layer of resist. After the
previous steps are redone, the SiO$_2$ can be etched in hydrofluoric acid (HF). Again the AlN fully etched in the solution. This can be prevented by again protecting the front-side with an adjusted resist. Please note that the steps in this paragraph are unnecessary for the diamond-coated wafers, as no SiO$_2$ is present on these samples. The DRIE-etch mask for the Si-NCD wafers is an aluminum wet-etched layer. Al is etched by a slightly heated (35 – 45°C) solution of phosphoric acid, acetic acid, nitric acid and water with a resist that is exposed and developed with the membrane-mask.

The first diamond-wafer processed was coated with a (0.7 ± 0.3) $\mu$m thick diamond layer. The stress was determined with the “MX203 stressmeter” to be 4.8 MPa (compressive), which was a lot lower than expected. The stress in previous films was about 60 MPa. Therefore techniques in stress compensation were thought off: by deposition of a tensile stressed AlN$^1$ layer the buckling of

$^1$ Film stress in the “Nexx-systems Nimbus” is controlled by varying the degree of energetic
the membrane can be prevented. For stresses less than 5 MPa this procedure is thought to be irrelevant.

The wafer is now ready to be dry etched in the “Surface Technology Systems” DRIE etcher. This equipment is build for the etching of 8 inch wafers, and can etch 4 inch wafers if they are taped onto a 8 inch carrier. Therefore cooling during etching of 4 inch wafers is not optimal. In the DRIE etcher not only the back-side is etched, also the front-side will be etched. Therefore it needs to be protected by a resist. After the full etching of the silicon substrate, particle bombardment during sputtering. Tensile stress is reduced by increasing bombardment, through RF bias of substrates. Compressive stress is reduced, by sputtering at high pressures, which decreases bombardment of the film during deposition.
the membrane is released. During the DRIE etching some of the membranes already broke, and while trying to remove the protective resist on the front-side, more membranes failed (Figure 8.10). Not all resist was removed, to prevent the breaking of all membranes (Figure 8.11). A solution to this problem might be to capton tape all the sides of wafer on the carrier. This will prevent the front-side etching, and will eliminate the need for a protective resist on the front. Measurement of the devices without residues of resist and membranes that are still intact, shows shortcuts between top and ground layer (can also be due to shortcuts between the IDT-finger structures). New samples need to be started.

Figure 8.10: Broken diamond membrane (X1.25).

Figure 8.11: Protective resist on the front-side that was not removed (X1.25).

8.2 Cantilever beams

The cantilever device processes employ similar process techniques as in the fabrication of the FPW devices. The process flow is described in section 7.3.

In the first run 6 inch silicon wafers are used. A layer of TiW is deposited instead (100 nm) of Pt, since the Pt deposition tool was unavailable for a long time. After lift-off and resist removal, a layer of AlN can be deposited (350 nm)
and wet-etched. On top a layer of Al is deposited and again wet etched after the necessary lithography. Results are shown in Figure 8.12 and Figure 8.13. After the Al etch the exposed TiW was etched and connection to the contact pad was broken.

In the second run, a thin layer of Pt (50 nm) is deposited since the Pt deposition tool was available again. Lift-off for Pt is performed, then AlN is sputtered (350 nm) and wet etching is performed as in the previous run. An Al layer (1 µm) is deposited on top and etched. The Al on Pt contact had a strange appearance due to stress differences in both layers: Figure 8.14.

After front and back dry etching the cantilever beams are released and can be measured. All beams had shortcuts between ground layer (Pt) and top layer (Al). Further investigations show that the 50 µm overlap of the AlN between the Pt and the Al has broken off during the etching and/or during front-resist removal (Figure 8.15). This can cause the shortcuts. Tests are done to investigate the slope of the dry etch: Figure 8.16 shows SEM images for the FPW devices etched with the same dry etch process. A new etch-recipe is written to improve the etch-slope.

In the meantime more wafers are started in the process flow to produce new samples. However, there were problems in the deposition tool of the AlN. The vacuum pumps were not working correctly and the plasma could not be kept stable. AlN was deposited as good as possible. However in processing this AlN layer is removed in the “microstrip” bath, a step that had gone perfectly before, this is probably due to the bad quality of this deposition. Since other projects also encounter shortcut problems in the AlN material, more specific tests need to be done in order to investigate the materials properties. The latest investigations show that AlN sputtered with a bias power, all result in “leaky” AlN: shortcuts between ground and top metal. The AlN sputtered without bias power seems ok.
Lift-off resist for TiW:

After lift-off of TiW:

Figure 8.12: Patterned resist for lift-off and TiW layer after lift-off.
Figure 8.13: *After the AlN etch and Al etch: TiW-contacts etched.*
Figure 8.14: After the AlN etch and Al etch: Al on Pt stress differences.

Figure 8.15: After dry etching and resist removal: AlN overlap removed, causing shortcuts between ground and top layer.
Figure 8.16: SEM images of the FPW membrane dry etch slope: a) Logo, b) Si edge on the NC-diamond membrane, c)/d) underetch of the Si, the Al mask is curling down over the edge.


Discussion of Results and Conclusions

9.1 Results and conclusions

Flexural plate wave sensors are thought to be sensors with excellent capabilities. They have a higher expected sensitivity than sensors based on other transduction principles. The ability to operate at a low phase velocity makes it a good candidate for biosensing, since this makes it able to operate in a liquid environment.

Exploring the provided model made it possible to conclude that the material for the plate must have a high material constant \( \alpha \) and a low mass per unit of area, for a good mass detection limit. These conditions imply that small layer thicknesses \( d \) should be employed, and materials should be used with a high Young’s modulus \( E \), a low Poisson’s ratio \( \nu \) and a low density \( \rho \).

This leads to the use of nanocrystalline diamond as waveguide layer, aluminum nitride as piezoelectric material, and aluminum as a conducting metal because of their high material constant. The aluminum was replaced by platina for its easier processing. This caused only a rather small drop in sensitivity.

Other important parameters for the design are the wavelength \( \lambda \), the plate length \( l \) and the plate width \( b \). Where \( \lambda \) is to be taken small for optimal sensing as derived in the model, and in the same time not too small for dispersion of the wave in the liquid. For our design this energy trapping condition is taken as \( \lambda \geq 40 \text{ } \mu\text{m} \), which should satisfy the energy trapping condition \( \lambda > \frac{4\hbar}{v_F} \). It has been shown that the plate’s width \( b \) has no influence for reasonable values (an example is shown in Figure 4.1).

Further simulation of different combinations of plate length \( l \) and mode number \( n \) has confirmed that devices designed with the lowest wavelength have the highest sensitivity. In this specific case the device with a plate length of 2000 \( \mu\text{m} \) and a mode number \( n \) of 100 had the highest sensitivity of 27.7 \( \text{m}^2/\text{kg} \) for a waveguide layer thickness of 1 \( \mu\text{m} \). This device (labelled G40.20) has a wavelength of 40 \( \mu\text{m} \).

Comparison is made between silicon dioxide and nanocrystalline diamond as waveguide layer, for sensitivity both in air as in liquid environment. Also comparison is made for the torque per unit of voltage. Both cases report the nanocrystalline diamond as the better material for the flexural plate wave sen-
sor's mass detection limit.

A design is made in order to microprocess these sensors. The device consists of 5 layers:

**1. Substrate:** support for the FPW membrane layers, and handling (e.g. Silicon).

**2. Waveguide layer:** a layer with the better material for the propagation of the waves (e.g. NCD).

**3. Ground layer:** an electrical ground for the transducers electrical signals (e.g. Pt).

**4. Piezoelectric layer:** for actuation and detection of the waves in the plate (e.g. AlN).

**5. Top metal layer:** in the form of an ITD structure for electrical actuation and detection of the waves (e.g. Pt).

Three mask layers are needed. The first mask layer is the contact pad mask, it is used to make an opening in the piezoelectric layer to the metal ground layer underneath. The second mask layer is the top metal mask and this one is used to pattern the resist for lift-off of the top metal layer, in order to obtain the IDT-comb structure. The third mask layer is the membrane mask and is used to pattern the Al hard mask for DRIE etching the substrate.

Both rectangular and round plates were designed. The rectangular device is conformal with the more conventional FPW design, the round structure was thought off for reasons of stress concentration in the corners of the rectangular design. By lowering the stress concentration, it is intended to decrease the device fragility. The process flow is described in section 6.2.

To investigate the piezoelectric material used (aluminum nitride), a design for a cantilever beam was made. This beam will deflect when a voltage is applied over the piezoelectric material. By measuring this deflection the piezoelectric coupling coefficient can be determined.

Both the FPW devices and the cantilever beams required excessive processing. In the beginning a lot of small problems in the process flow needed to be solved. When the first devices were finished it seemed that they all had shortcuts between ground and top layer. Subsequently new devices were processed. As additional problems were encountered constantly, it was assumed that the AlN used had a bad quality. More tests are needed to confirm the actual reason of the returning problems. Latest results show that AlN sputtered without a bias power does not have shortcuts for a simple capacitive structure. Results for the cantilever beams can hopefully be expected soon.
9.2 Future outlook

Up to now no working device has been presented, even large efforts could not make it happen in this time-frame. After additional investigation of the aluminum nitride, and optimization of its quality, the processing can be restarted in order to obtain working cantilever beams. Afterwards the determination of the piezoelectric coefficient of the aluminum nitride can be done. This can be used to characterize the operation of the flexural plate wave device in air. Questions still remain how this flexural plate wave device can be handled in a liquid environment and how it can be characterized for its reaction to additional mass on the plate while immersed in the liquid. In addition to this surface bio-functionalization is needed for the operation as biosensor.
References


REFERENCES


Appendix A: MATLAB® implementation of the FPW model

In this appendix, the complete model for the FPW device is implemented in MATLAB®. See also Chapter 4 for results of these calculations.

\[ y_M \]
returns the neutral axis for multiple layer structure

\[
\text{function } y_M = f(E, \text{nu}, \text{dikte, b})
\]
- Given: \( y \) of all layers - take the bottom of the plate as the arbitrary reference point -
- \( E \) of all layers -
- \( \nu \) of all layers -
- \( A = \text{layer cross sectional area (thickness times width)} \)

\[ y_{Mteller} = 0 \]
\[ y_{Mnoemer} = 0; \]
\[ q = 1; \]
\[ y_1 = y(\text{dikte}); \]
\[ A = A(\text{dikte}, b); \]
\[ N = \text{size(dikte, 2)}; \]
while \( q < N + 1 \)
\[ y_{Mteller} = y_{Mteller} + ((y_1(q) \times E(q) \times A(q))/(1 - \text{nu}(q)^2)); \]
\[ y_{Mnoemer} = y_{Mnoemer} + ((E(q) \times A(q))/(1 - \text{nu}(q)^2)); \]
\[ q = q + 1; \]
end
\[ y_M = y_{Mteller}/y_{Mnoemer} \]

\[ D \]
Rigidity of the multiple layer structure

- \( A_i = \text{thickness times width} \)

\[
\text{function } D = f(E, \text{nu}, \text{dikte, b})
\]
\[ I = \text{b \times derdemacht(dikte)/12;} \]
\[ Y = y(\text{dikte}) - y_M(E, \text{nu}, \text{dikte, b}); \]
\[ D = 0; \]
\[ q = 1; \]
\[ A = \text{dikte \times b}; \]
\[ N = \text{size(dikte, 2)}; \]
while \( q < N + 1 \)
\[ D = D + (E(q) \times (I(q) + A(q) \times Y(q)^2))/(1 - \text{nu}(q)^2); \]
\[ q = q + 1; \]
end
\[ D \]

\[ fnj \]
returns the frequencies for multiple layer structure

\[
\text{function } fnj = f(n, \text{mode}, L, b, E, dikte, nu, \text{ro})
\]
\[ G_n = n + 1/2; \]
\[ J_n = (n + 1/2) \times (1 - 2/(\pi \times (n + 1/2))); \]
\[ G_j = \text{mode + 1/2}; \]
\[ J_j = (\text{mode + 1/2}) \times (1 - 2/(\pi \times (\text{mode + 1/2}))); \]
\[ fnj = \text{pi}/2 \times \text{sqrt}((G_n^2/L^4 + G_j^2/b^4 + 2 \times J_n \times J_j/(L^2 \times b^2)) \times \text{sqrt}(D(E, \text{nu}, \text{dikte, b})/(b \times \text{ma(dikte, ro))}) \]

\[ \text{ma} \]
mass/area of the multiple layer structure

\[
\text{function } \text{ma} = f(\text{dikte, ro})
\]
\[ \text{ma} = \text{sum(\text{serm(dikte, ro))}) \]

\[ A \]
cross sectional area: thickness times width
function \( A = f(d\text{ikte}, b) \)
\( A = d\text{ikte} \times b \)

y

function \( y = f(d\text{ikte}) \)
\( q = 1; \)
\( \text{somlagen} = 0; \)
while \( q < N + 1 \)
\( y(q) = \text{somlagen} + d\text{ikte}(q)/2; \)
\( \text{somlagen} = \text{somlagen} + d\text{ikte}(q); \)
\( q = q + 1; \)
end

\( y \)

massa

returns mass/area for each thickness of the diamond

function \( \text{massa} = f(dNCD, \text{ro}, d\text{ikte}) \)
\( q = 1; \)
\( \text{aantalpnt} = \text{size}(dNCD, 2); \)
while \( q < \text{aantalpnt} + 1 \)
\( d\text{ikte}(1) = dNCD(q); \)
\( \text{massa}(i) = \text{sum}((\text{verm(\text{ro}, d\text{ikte}))}); \)
\( q = q + 1; \)
end

\( \text{massa} \)

freq

returns frequency for each thickness of the diamond

function \( \text{freq} = f(dNCD, n, j\text{mode}, L, b, E, d\text{ikte}, \text{nu}, \text{ro}) \)
\( q = 1; \)
\( \text{aantalpnt} = \text{size}(dNCD, 2); \)
while \( q < \text{aantalpnt} + 1 \)
\( d\text{ikte}(1) = dNCD(q); \)
\( \text{freq}(q) = \text{fnj(n, jmode, L, b, E, dikte, nu, ro}); \)
\( q = q + 1; \)
end

\( \text{freq} \)

vp

phase velocity for each thickness of diamond

function \( \text{vp} = f(dNCD, n, j\text{mode}, L, b, E, d\text{ikte}, \text{nu}, \text{ro}) \)
\( i = 2 \times \frac{L}{n} \)
\( \text{vp} = 1 \times \text{freq}(dNCD, n, j\text{mode}, L, b, E, d\text{ikte}, \text{nu}, \text{ro}) \)

\( S_A \)

Sensitivity in AIR for each thickness of the diamond

function \( S_A = f(dNCD, n, j, L, b, E, d\text{ikte}, \text{nu}, \text{ro}) \)
\( N = \text{size}(dNCD, 2); \)
\( X\text{massa} = \text{massa}(dNCD, \text{ro}, d\text{ikte}); \)
\( Y\text{freq} = \text{freq}(dNCD, n, j, L, E, d\text{ikte}, \text{nu}, \text{ro}); \)
\( i = 1; \)
while \( i < N \)
\( S_A(i) = ((Yfreq(i + 1) - Yfreq(i))/((Xmassa(i + 1) - Xmassa(i)))/Yfreq(i)); \)
\( i = i + 1; \)
end
\( S_A(N) = S_A(N - 1) \times Yfreq(N - 1)/Yfreq(N); \)

\( S_L \)

Sensitivity in Liquid for each thickness of diamond

function \( S_L = f(dNCD, n, j\text{mode}, L, b, E, d\text{ikte}, \text{nu}, \text{ro}) \)
\( S_A = \text{gradient(freq(dNCD, n, j\text{mode}, L, b, E, dikte, nu, ro), 8.6507e-006);} / \text{freq(dNCD, n, j\text{mode}, L, b, E, dikte, nu, ro);} \)
\( S_L = 1; \)
\( \text{while } q < N + 1 \)
\( S3(q) = 1/S2(q); \)
\( q = q + 1; \)
end
\( S3 \)

\( S_L = -S3 \)

\( \Delta \)

Decay length
Appendix A

\begin{verbatim}
function delta = f(dNCD, dikte, n, jmode, L, b, E, nu, ro, vf)
l = 2 * L/n;
deltaym = abs(dikte(l) + dikte(2) + (dikte(3)/2) - yM(E, nu, dikte, b));
hp = dikte(3);
nup = nu(3);
A = hp * b;
M = (E(3) * deltaym * A * d31)/(hp * (1 - nup));
end

function onlyreal = f(K)
N = size(K, 2);
q = 1;
while q < N + 1
    onlyreal(q) = isreal(K(q)) * K(q);
    q = q + 1;
end

function plotfvsb = f(differentvalues, n, jmode, L, E, dikte, nu, ro)
N = size(differentvalues, 2)
counter = 1;
while counter < N + 1
    andereb = differentvalues(counter);
    fnj(n, jmode, L, andereb, E, dikte, nu, ro);
    plotfvsb(counter) = fnj(n, jmode, L, andereb, E, dikte, nu, ro);
    counter = counter + 1;
end

function plotSvsn = f(dNCD, dikte, n, roF, L, b, E, nu, ro, vF, jmode)
q = 1;
whileq < 200
    n = q;
P = SL(dNCD, dikte, n, roF, L, b, E, nu, ro, vF, jmode);
P330 = P(330);
plotSvsn(q) = P(330);
q = q + 1;
end

function y = f(x)
q = 1;
aantal = size(x);
while q < aantal(2) + 1
    y(q) = x(q)^2;
    q = q + 1;
end

function y = f(a, b)
q = 1;
N = size(a, 2);
while q < N + 1
    y(q) = a(q) * b(q);
    q = q + 1;
end

function y = f(x)
q = 1;
aantal = size(x);
while q < aantal(2) + 1
    y(q) = x(q)^3;
    q = q + 1;
end

function M = f(E, nu, dikte, b, d31)
deltaym = abs(dikte(1) + dikte(2) + (dikte(3)/2) - yM(E, nu, dikte, b));
hp = dikte(3);
nup = nu(3);
A = hp * b;
M = (E(3) * deltaym * A * d31)/(hp * (1 - nup));
end
\end{verbatim}
plotM
plots the torque vs the thickness of the wave-guiding layer

function plotM = f(dNCD, E, nu, dikte, b, d31)
i=1;
hold on
while i < 1001
    dikte(1) = dNCD(i);
    h = dikte(1) + dikte(2) + dikte(3) + dikte(4)
    plot(h, 1/Mp(E, nu, dikte, b, d31), 'g')
    i = i + 1;
end

plotV
plots the voltage as 1/M vs the thickness of the wave-guiding layer

function plotV = f(dNCD, E, nu, dikte, b, d31)
i=1;
hold on
while i < 1001
    dikte(1) = dNCD(i);
    h = dikte(1) + dikte(2) + dikte(3) + dikte(4)
    plot(h, abs(Mp(E, nu, dikte, b, d31)), 'g')
    i = i + 1;
end

plotfvsb
plots the frequency vs the plate width

function plotfvsb = f(dNDCfreq, jmode, E, dikte, nu, ro)
L = 500 * 10^(-6)
while L < 8000 * 10^(-6)
    b = L/2
    hold on
    if L == 500 * 10^(-6)
        n = 20
        plot(dNCDfreq, freq(dNCDfreq, jmode, E, dikte, nu, ro), 'g')
    elseif L == 1000 * 10^(-6)
        n = 50
        plot(dNCDfreq, freq(dNCDfreq, jmode, E, dikte, nu, ro), 'r-')
    elseif L == 2000 * 10^(-6)
        n = 80
        plot(dNCDfreq, freq(dNCDfreq, jmode, E, dikte, nu, ro), 'r')
        n = 100
        plot(dNCDfreq, freq(dNCDfreq, jmode, E, dikte, nu, ro), 'k-')
    elseif L == 4000 * 10^(-6)
        n = 50
        plot(dNCDfreq, freq(dNCDfreq, jmode, E, dikte, nu, ro), 'b')
        n = 80
        plot(dNCDfreq, freq(dNCDfreq, jmode, E, dikte, nu, ro), 'g-')
    elseif L == 8000 * 10^(-6)
        n = 20
        plot(dNCDfreq, freq(dNCDfreq, jmode, E, dikte, nu, ro), 'c-')
    end
end

plotdNCDfreq
plots the frequency vs the thickness of the wave-guiding layer

function plotdNCDfreq = f(dNCDfreq, jmode, E, dikte, nu, ro)
L = 500 * 10^(-6)
while L < 8000 * 10^(-6)
    b = L/2
    hold on
    if L == 500 * 10^(-6)
        n = 20
        plot(dNCDfreq, freq(dNCDfreq, jmode, E, dikte, nu, ro), 'g')
    elseif L == 1000 * 10^(-6)
        n = 50
        plot(dNCDfreq, freq(dNCDfreq, jmode, E, dikte, nu, ro), 'r-')
    elseif L == 2000 * 10^(-6)
        n = 80
        plot(dNCDfreq, freq(dNCDfreq, jmode, E, dikte, nu, ro), 'r')
        n = 100
        plot(dNCDfreq, freq(dNCDfreq, jmode, E, dikte, nu, ro), 'k-')
    elseif L == 4000 * 10^(-6)
        n = 50
        plot(dNCDfreq, freq(dNCDfreq, jmode, E, dikte, nu, ro), 'b')
        n = 80
        plot(dNCDfreq, freq(dNCDfreq, jmode, E, dikte, nu, ro), 'g-')
    elseif L == 8000 * 10^(-6)
        n = 20
        plot(dNCDfreq, freq(dNCDfreq, jmode, E, dikte, nu, ro), 'c-')
    end
end
function plotdNdCDoverlambdaSL = f(dNCD, dikte, n, roF, E, nu, ro, vF, jmode)
L = 500 \times 10^{-6}
while L < 8000 \times 10^{-6}
    b = L/2
    n = 20
    lambda = 2 \times L/n
plot(dNCD/lambda, abs(onlyreal(S_L(dNCD, dikte, n, roF, L, b, E, nu, ro, vF, jmode))))
else if L == 1000 \times 10^{-6}
    n = 50
    lambda = 2 \times L/n
plot(dNCD/lambda, abs(onlyreal(S_L(dNCD, dikte, n, roF, L, b, E, nu, ro, vF, jmode))))
else if L == 2000 \times 10^{-6}
    n = 80
    lambda = 2 \times L/n
plot(dNCD/lambda, abs(onlyreal(S_L(dNCD, dikte, n, roF, L, b, E, nu, ro, vF, jmode))))
else if L == 4000 \times 10^{-6}
    n = 100
    lambda = 2 \times L/n
plot(dNCD/lambda, abs(onlyreal(S_L(dNCD, dikte, n, roF, L, b, E, nu, ro, vF, jmode))))
else if L == 8000 \times 10^{-6}
    n = 150
    lambda = 2 \times L/n
plot(dNCD/lambda, abs(onlyreal(S_L(dNCD, dikte, n, roF, L, b, E, nu, ro, vF, jmode))))
end
L = L*2
end
plotdNCDSL
plots $S_L$ for all devices vs dNCD

function plotdNCDSL = f(dNCD, dikte, roF, E, nu, ro, vF, jmode)
L = 500 * 10^(-6)
while L < 8000 * 10^(-6)
    b = L/2
    hold on
    if L <= 500 * 10^(-6)
        n = 20
        plot(dNCD, abs(realimag(SL(dNCD, dikte, n, roF, L, b, E, nu, ro, vF, jmode))), 'g')
        else if L == 1000 * 10^(-6)
            n = 50
            plot(dNCD, abs(realimag(SL(dNCD, dikte, n, roF, L, b, E, nu, ro, vF, jmode))), 'r--'
        else if L == 2000 * 10^(-6)
            n = 80
            plot(dNCD, abs(realimag(SL(dNCD, dikte, n, roF, L, b, E, nu, ro, vF, jmode))), 'g--'
        else if L == 4000 * 10^(-6)
            n = 100
            plot(dNCD, abs(realimag(SL(dNCD, dikte, n, roF, L, b, E, nu, ro, vF, jmode))), 'k')
        else if L == 8000 * 10^(-6)
            n = 150
            plot(dNCD, abs(realimag(SL(dNCD, dikte, n, roF, L, b, E, nu, ro, vF, jmode))), 'b--'
        end
    end
end
L = L^2
plotdNCDSL = 1;

plotdNCDSA
plots $S_A$ for all devices vs dNCD

function plotdNCDSA = f(dNCD, dikte, roF, E, nu, ro, vF, jmode)
L = 500 * 10^(-6)
while L < 8000 * 10^(-6)
    b = L/2
    hold on
    if L <= 500 * 10^(-6)
        n = 20
        plot(dNCD, S_A1(dNCD, n, jmode, L, b, E, dikte, nu, ro))
        else if L == 1000 * 10^(-6)
            n = 50
            plot(dNCD, S_A1(dNCD, n, jmode, L, b, E, dikte, nu, ro))
        else if L == 2000 * 10^(-6)
            n = 100
            plot(dNCD, S_A1(dNCD, n, jmode, L, b, E, dikte, nu, ro))
        else if L == 4000 * 10^(-6)
            n = 20
            plot(dNCD, S_A1(dNCD, n, jmode, L, b, E, dikte, nu, ro))
        end
    end
end

$n = 50$
plot(dNCD, SA1(dNCD, n, jmode, L, b, E, dikte, nu, ro))
n = 80
plot(dNCD, SA1(dNCD, n, jmode, L, b, E, dikte, nu, ro))
n = 100
plot(dNCD, SA1(dNCD, n, jmode, L, b, E, dikte, nu, ro))
n = 150
plot(dNCD, SA1(dNCD, n, jmode, L, b, E, dikte, nu, ro))

else if $L = 8000 \times 10^6$

$n = 20$
plot(dNCD, SA1(dNCD, n, jmode, L, b, E, dikte, nu, ro))
n = 50
plot(dNCD, SA1(dNCD, n, jmode, L, b, E, dikte, nu, ro))
n = 80
plot(dNCD, SA1(dNCD, n, jmode, L, b, E, dikte, nu, ro))
n = 100
plot(dNCD, SA1(dNCD, n, jmode, L, b, E, dikte, nu, ro))
n = 150
plot(dNCD, SA1(dNCD, n, jmode, L, b, E, dikte, nu, ro))

end

end

end

L = L^2
plotdNCDSA = 1;
Appendix B: Calculations of Plate’s area, width, wavelength and finger spacing

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<td>8100</td>
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Table B.1: Plate’s area, width, wavelength and finger spacing.
Appendix C: Frequencies for round devices

The fundamental mode frequency for a round membrane is given by [3]:

\[ f = \frac{\lambda^2}{2\pi^2} \sqrt{\frac{E d^3}{12 m_a (1 - \nu^2)}} \]  

(C.1)

where \( \lambda \) is the wavelength given by \( 2D \) with \( D \) the diameter of the round FPW device; \( r \) is the membrane radius; \( d \) is the plate thickness; \( m_a \) is the plate’s mass per unit area, calculated by multiplying the materials density and thickness of the plate; \( E \) is the materials Young’s modulus and \( \nu \) is the Poisson’s ratio.

For a simple 1-layer diamond plate, the frequencies are calculated in table C.2.

<table>
<thead>
<tr>
<th>Round ID</th>
<th>ID</th>
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<th>R4000.2</th>
<th>R2000.1</th>
<th>R2000.2</th>
<th>R1000.1</th>
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<tbody>
<tr>
<td>D [( \mu m )]</td>
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<td>4000</td>
<td>4000</td>
<td>2000</td>
<td>2000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>R [( \mu m )]</td>
<td>53</td>
<td>2000</td>
<td>2000</td>
<td>1000</td>
<td>1000</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>r [( \mu m )]</td>
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<td>600</td>
<td>700</td>
<td>300</td>
<td>350</td>
<td>150</td>
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<td>r/R</td>
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<td>0.3</td>
<td>0.7</td>
<td>0.3</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
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<td>8000</td>
<td>4000</td>
<td>4000</td>
<td>2000</td>
<td>2000</td>
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<td>f [Hzm(^2)]</td>
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<td>0.027</td>
<td>0.15</td>
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<td>Area ([m^2])</td>
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<td>7.1E-07</td>
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<tr>
<td>f/A [kHz]</td>
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<td>17</td>
<td>51E+1</td>
<td>70</td>
<td>21E+2</td>
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</table>

<table>
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<th>R500.2</th>
<th>R100.1</th>
<th>R100.2</th>
<th>R50.1</th>
<th>R50.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>D [( \mu m )]</td>
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<td>500</td>
<td>500</td>
<td>100</td>
<td>100</td>
<td>50</td>
<td>50</td>
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<td>R [( \mu m )]</td>
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<td>250</td>
<td>50</td>
<td>50</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>r [( \mu m )]</td>
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<td>75</td>
<td>35</td>
<td>15</td>
<td>17.5</td>
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<tr>
<td>r/R</td>
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<td>0.3</td>
<td>0.7</td>
<td>0.3</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>( \lambda [\mu m] )</td>
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<td>1000</td>
<td>200</td>
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<td>100</td>
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<td>f [Hzm(^2)]</td>
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<td>0.027</td>
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<tr>
<td>f/A [kHz]</td>
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<td>42</td>
<td>70E+2</td>
<td>21E+4</td>
<td>28E+3</td>
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Table C.2: Frequencies calculated for a simple 1-layer diamond round membrane device.