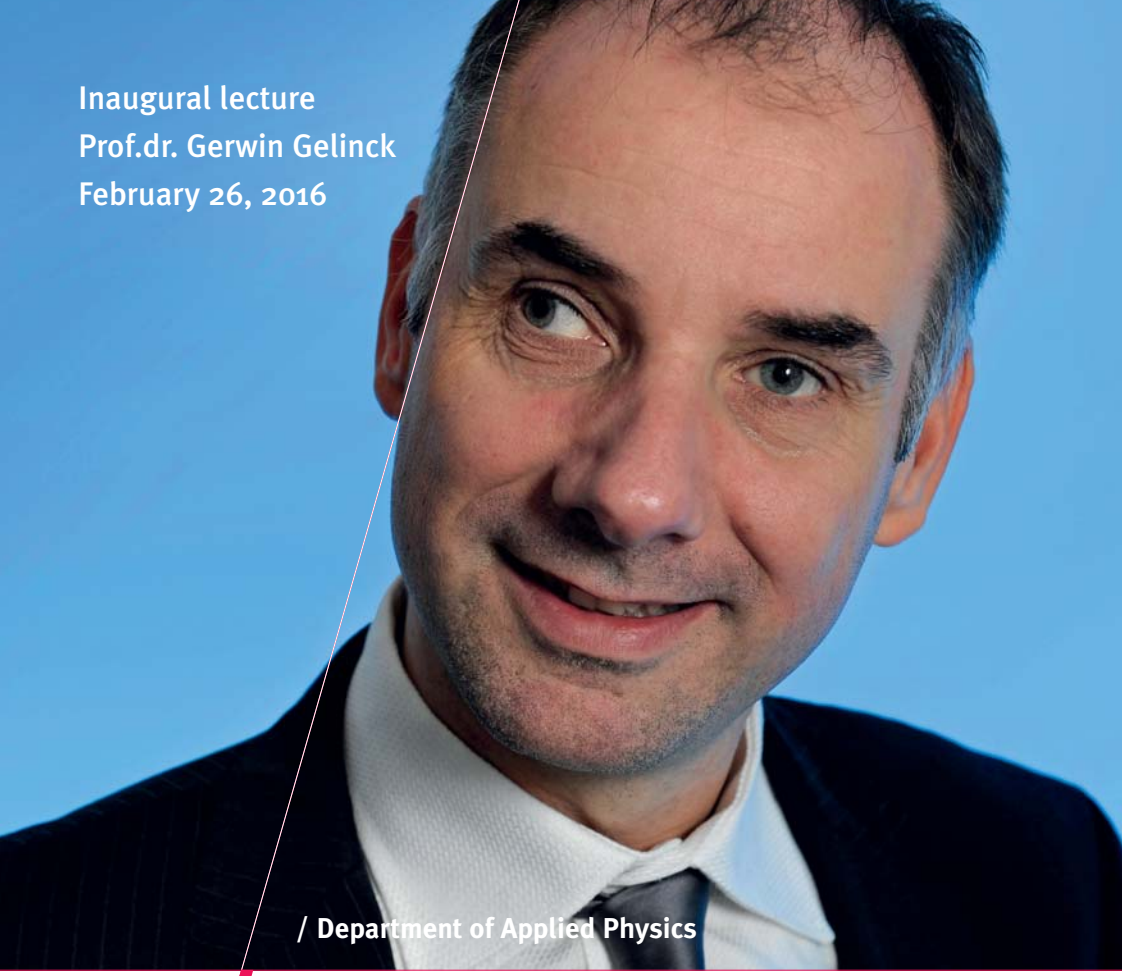
Flexible large-area electronics : electronics for everybody, on the body and in the body



Inaugural lecture
Prof.dr. Gerwin Gelinck
February 26, 2016

/ Department of Applied Physics

TU/e Technische Universiteit **Eindhoven** University of Technology

Flexible, large-area electronics

Electronics for everybody, on the body and in the body

Where innovation starts

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Presented on February 26, 2016
at Eindhoven University of Technology

Introduction

Mijnheer de Decaan, leden van het College van Bestuur, collegae hoogleraren en andere leden van de universitaire gemeenschap, zeer gewaardeerde toehoorders, dames en heren,

As the Dean mentioned, this speech marks the creation of the chair in Flexible, large-area electronics at this University. In this talk, I would like to share with you my excitement for this field and show you how thin-film transistors made from organic or metal oxide semiconductors (TFTs) can be combined with plastic foil substrates to deliver thinner, more flexible devices than today's silicon or glass-based electronics.

Flexible and printed TFTs are important for a broad range of applications. Today, the long-held dream of rollable and foldable displays drives most innovation in this area. But as technologies mature, other flexible electronic applications will undoubtedly emerge, possibly in areas such as medical X-ray detectors, electronic skin and retinal implants.

I will also explain how flexible electronics draws on equipment, design and manufacturing processes from three established industries: semiconductor, display and graphic printing. And I will give examples of how new *soluble* electronic materials enable novel fabrication processes and device concepts. A better understanding of these materials and devices – their potential and limitations – is key to delivering next-generation mobile and wearable electronics.

Flexible, large-area electronics

Electronics for everybody

Silicon electronics is getting significantly more powerful and cheaper every year. It is hard to overstate this trend. So let me give you an illustration: a 32 GB smartphone that retails for a few hundred Euros today would have cost more than 4 billion dollars in 1976! [1]

Technical innovations and economies of scale have made electronics affordable for everybody – resulting in today's information age. From the Internet of Things to health monitoring and lifestyle tracking, the connected world will be driven by electronic information. People will need to review and interact with that data at home, at work and on the go. And to do that, we will need displays that go wherever we do. Displays are the primary "face" of the computing, communications and entertainment systems that have become ubiquitous in our daily lives.

Silicon microprocessors and displays are so good and so cheap that you might think there is no need for other technologies. But we mustn't fall into the trap of thinking they can solve every problem. Could a silicon-based iPhone roll up to fit in your pocket? Could it survive a fall from this desk to the ground? Probably not.

Figure 1

Flexible, large-area electronics draws equipment, design and manufacturing processes from three established industries: semiconductor, display and graphic printing.

Why flexible?

As well as becoming more powerful and cheaper, electronics is becoming continually smaller. History tells us that electronic devices decrease in size and weight by a factor of 10 every 10 years [2]. In a few decades, we have gone from

room-sized mainframes to pocket-sized mobile phones. Conversely, mobile phone screens are getting bigger. That makes them more prone to breakage. And even if you didn't pay 4 billion dollars, that would be a shame.

How can we continue to address these two trends simultaneously? The answer lies in a new generation of mechanically flexible, foil-based displays. They could be as large as you want when in use, and then rolled or folded away when not needed. Such displays also wouldn't break if you drop them.

The idea of a display you can simply fold up and put in your pocket was pioneered in the early 2000s by Philips Research [3]. This activity was spun off 5 years later into a company called Polymer Vision. Polymer Vision has since ceased to exist but the idea is still very much alive. Korean display makers have already brought curved mobile phones screens to the market. These screens are in fact made on plastic substrates and then covered with a thin glass substrate for protection. Although not flexible themselves, they are an important step towards mechanically flexible displays.

Figure 2

Prototypes of rollable, foldable and stretchable displays. Source: Holst Centre.

Mechanically flexible, foil-based displays also open up all sorts of new applications. For example, their high-density electrical integration over large areas is very much sought after for large photo-imagers – in particular medical X-ray detectors. Modern digital X-ray systems offer many benefits over older analog ones. Images are available faster, are easier to share and can be achieved with less radiation. Since their introduction in the nineties, these systems have employed detectors made on glass substrates with amorphous silicon thin-film transistors and diodes. This makes them heavy, difficult to transport and easy to break. Flexible, plastic substrates could enable lighter, more robust and less expensive X-ray systems that are easier to move around in the hospital. The X-ray machine could be brought to the patient rather than the other way around. Large, curved X-ray detectors could simplify fabrication and improve sensitivity for CT (computed tomography) systems as well.

Three years ago, Holst Centre and Philips Medical were the first to show a prototype digital X-ray detector on plastic in which all layers except the electrodes were solution processed [4]. By using a solution-processed organic semiconductor rather than the usual amorphous silicon, we could reduce process temperatures to be compatible with polyester substrates. At the same time, we eliminated a number of costly lithography steps, opening the door to lower production costs.

Since then, we have improved organic photodetector sensitivity by a factor of 10,000, bringing it well within the requirements for medical detectors [5]. This improves the signal-to-noise ratio, and hence image quality at low radiation dose. Meanwhile, we have moved from organic to metal-oxide TFTs which have 10-50 times higher charge carrier mobility – enabling faster image acquisition.

Why printing?

Many of the material and device performance requirements for flexible electronics have already been met. Hence, current research is moving towards areas such as low-cost manufacturing techniques for high-volume, low-cost disposable applications. Most researchers agree that printing is an ideal way to do that. Different inks could be printed onto the plastic foil and as they dried they would turn into functional devices and all the other things required for displays and circuits.

At least, that's the theory. But as anyone who has ever seen a blurry newspaper photo knows, printing isn't always precise. For flexible electronics, poor alignment between different layers would kill any chance of a functioning device. The required overlay accuracy in any transistor process is of the order of microns or better. What's more, the error tolerance for electronics is much tighter than for photos. Then there are the materials themselves. Can they actually be printed? How do we form them into the precise structures we need?

Despite these questions, the prospect of replacing the high-cost techniques currently used to grow semiconductor layers in state-of-the-art TFTs with cheaper methods is so attractive from both business and environmental standpoints that a large research community is working on it – including Holst Centre. The ultimate goal is to print simple electronic circuits that bring intelligence and interactivity to a wide range of applications in form factors that aren't possible with silicon chips. For example, low-cost electronic labels for the highly price-sensitive logistics market [6] or low-speed microprocessors that can be programmed after manufacture via inkjet printing [7].

Research plans

We have seen that implementing flexible organic and oxide transistors, circuits and sensors on plastic substrates has great potential for displays and large area imagers. I believe the same technology could deliver brand new applications that today seem like science fiction. Like the interactive surfaces from the film *Minority Report* or smart bandages that monitor and accelerate wound healing (conceived in Holst Centre's *Future Sketches* in 2005). I also expect low-cost smart sensor labels to become available for food packaging, increasing food quality and shelf life.

This vision is gradually becoming a reality thanks to continuing innovation in low-temperature-processed organic and oxide TFT technology. However, the limited palette of available sensor devices and large process variations in TFT fabrication have so far limited the complexity of flexible circuits. Moreover, most TFT technologies still use photolithography fabrication processes. Fully printed organic circuits are needed to adequately demonstrate the ultra-low-cost potential of flexible electronics. Both areas require additional research.

In the remainder of this lecture I will explain my plans for this new chair. These can be broadly split into two: opening new application areas in the healthcare domain, and improving thin-film transistor performance through new materials, processes and devices.

Healthcare applications

Electronics on the body

Biometric sensing to help us understand what is happening inside our bodies is essential for diagnosing illness and managing health. For maximum accuracy, sensors should be in direct contact with our bodies and be as comfortable as possible. This raises the daunting challenge of directly interfacing electronics with human skin. The hard, brittle, inflexible silicon circuits that work so well in many areas struggle here – they just can't stretch and flex like skin does, reducing signal quality. Moreover, box-type electronics is heavy and obtrusive to wear, and prone to falling off. Flexible organic electronics has the potential to conform much more

closely to our bodies, and many researchers are actively fabricating electronic components on flexible and/or elastic substrates.

Groups such as those of John Rogers and Zhenan Bao in the US and Someya and Sekitani in Japan are carrying out inspiring and pioneering work in this field. Rogers and Someya/Sekitani have demonstrated multi-electrode arrays that record electrical signals from the brain, heart or muscles. The first implementations used silicon and III-V electronic devices (sensors, antennas, light-emitters, photodetectors and transistors) between two thin (7 µm) polyimide layers on a 30 µm rubber substrate. The elastic properties of this system match those of skin [8].

Recently, similar skin-wearable circuits and sensors have been made from thin-film organic semiconductors. Figure 3 shows a 64-channel electromyogram (muscle activity) sensor array with local amplifiers, made with organic TFTs. Integrated intimately on skin, this system has shown satisfactory signal-to-noise levels [9].

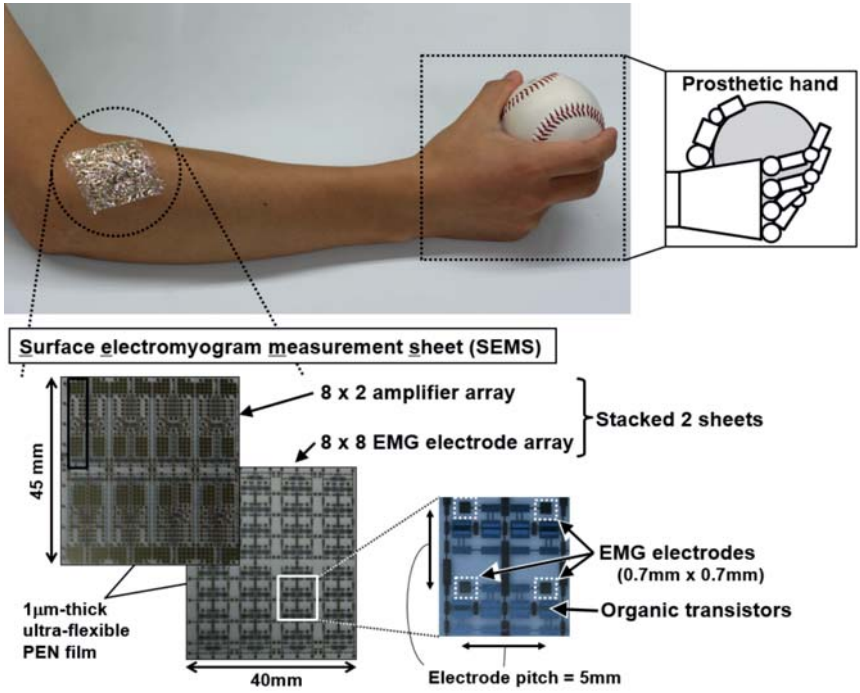

Figure 3

Electromyogram sensor array with organic semiconductor thin-film amplifiers on ultra-thin foil attached to skin. From [9].

More recently, Someya's group demonstrated large-scale arrays of conformal temperature sensors which measure milli-kelvin-scale physiological thermal events including respiration, blood flow through arteries and local muscle activity [10].

Whether it's called electronic skin, electronic tattoos or imperceptible electronics and whether you measure pressure, temperature or bio-potentials, all these applications need soft, flexible and bio-compliant electronics. They require distributed sensing and actuating over large areas, typically consisting of multi-electrode arrays that can measure the small and slow bio-signals. And circuits must adhere to the contours of the skin. Such ultra-thin electronic structures represent a major mechanical engineering challenge and put specific restraints on the materials used. Ideally, the inherent electrical performance of the semiconductor should be insensitive to applied strain [11]. Here, I want to have a look at the electronic design.

The thousands of sensors required for these applications could be addressed by a flexible switching matrix based on current organic and/or oxide TFT electronics. As the speed and performance of large-area TFTs isn't yet sufficient to process the vast amounts of sensor data generated, a small number of (CMOS) silicon chips is needed at the periphery of the matrix for further processing. The main role of the TFT in this solution is thus to reduce the connections to the silicon chips by multiplexing sensor signals.

While it is very useful, this approach breaks down for very large matrices with high numbers of sensors. In other words, it isn't scalable. For instance, long connections between sensor nodes and CMOS amplifiers at the edges of the sensing surface add parasitic capacitance that reduces the signal-to-noise ratio at the amplifier input. This would eventually limit performance in terms of minimum detectable signal. Adding CMOS amplifiers close to each sensor could help but would be expensive and may sacrifice the thin, flexible form factor.

Instead, we want the oxide transistors to provide amplification and convert analog sensor outputs to the digital domain. Local processing close to the sensor node, using oxide thin-film circuits, makes sense for numerous monitoring applications, be it pressure, temperature or light sensors. But developing circuitry that brings analog data to the digital domain is challenging. First, the technology is still developing, and the spread in device characteristics needs to be taken into account. Furthermore, accurate device models are still lacking. Progress in this

field requires close interaction between technology developers and electronic engineers with different backgrounds. We have therefore established active collaborations with the Electronic Engineering groups at the TU/e and imec.

In one project [12] we aim to support pregnant women by developing the electronics for a continuous electronic fetal monitoring (EFM) system that records electrophysiological signals via the mother's abdomen. Such systems already exist based on conventional box-type electronics. But they are mainly suited to hospital settings, sometimes forcing the woman to stay in bed. By making matrices stretchable and integrating them into fabrics, we plan to create embryo monitoring garments that expectant mothers can wear safely, discretely and comfortably in their normal daily life.

This work I will carry out together with Dr. Cantatore of the Mixed Signal Microelectronics Group of the Engineering Electronics Department of this university.

Electronics in the body

Arguably, the ultimate step is to interface organic electronics with biology and possibly living systems. This would make for truly unobtrusive healthcare applications and allow us to help people in ways that just aren't possible today. For example, age-related macular degeneration (AMD) and retinitis pigmentosa (RP) are two leading causes of blindness. Both are caused by malfunctioning photoreceptors in the retina, which should convert light to electrical signals. While the progress of these conditions can sometimes be slowed, there is currently no cure or way to restore lost sight.

Many research groups are currently working hard to develop implants for the vision impaired. [13] Clinical studies in 1996 showed it was feasible to stimulate the remaining retinal neurons by applying controlled electrical signals to a small area of the retina via a microelectrode, thereby allowing a small spot of light to be perceived. Currently, two microelectrode systems are at the clinical application stage. Both are powered through inductive coils, requiring complex surgical methods to implant the coil-decoder-cable-array systems that power the electrodes via intraocular cables.

Mathieson et al. have demonstrated a photovoltaic sub-retinal prosthesis consisting of a two-dimensional network of miniature silicon solar cells that directly stimulate the retina when illuminated by a goggle system [14]. This has the

great advantage over other approaches that no electrical power or data connection is required [15]. A MEMS-type process was used to create so-called silicon flexures that make the arrays curvable. This curvature means the whole implant is in focus, resulting in optimal visual perception. Curved implants can also be substantially larger than planar ones and can hence cover more of the field of view.

While these systems are already evidence of great progress, organic photovoltaic retina implants would offer a significant benefit. Their softness allows them to interface intimately with neurons so that electrical signals generated by organic (semi)conducting materials are translated into bio-signals. In 2011, Lanzani and co-workers in Italy successfully interfaced an organic photovoltaic with a network of primary neurons via a photoexcitation process [16]. These diodes could eventually be processed on very thin (less than 10 µm), flexible plastic films, making them highly suitable for retina implantation. It is even possible to make implants spherical by perforating the plastic film. Organic photodiodes absorb light efficiently and thus are typically much thinner than silicon diodes. This leads to a higher mechanical flexibility, and potentially higher pixel resolution. These advantages present a strong case for retinal implants based on organic photovoltaic arrays; however, this technology is still largely unexplored.

Inspired by this work, a PhD student is working on this topic since September last year. Progress is good as we can build on work being done at the university on organic solar cells, specifically photodiodes that are sensitive to near infrared (NIR) and water purification systems based on organic photovoltaics. For retinal implants, however, we need to take care that we use materials that remain unaltered after implantation in the human eye. This rules out water-soluble materials, electrode materials that corrode easily and, of course, anything toxic. Scientifically, this involves creating and studying interfaces that enable “electronics” in artificial systems to couple with the “ionics” of biological systems.

This process of restoring vision by transducing optical signals to electrically stimulate the neurons in the ‘image-processing’ inner retinal layers is just one example of the emerging scientific field that tries to create architectures that enable (bi)directional flow of information between man-made structures and living systems.

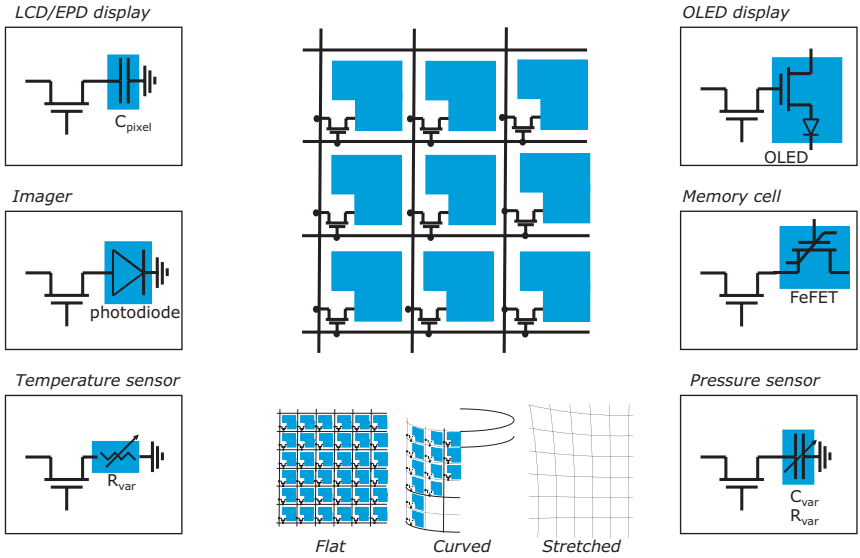

Figure 4

Transistor arrays can house thousands of individual pixels. Visual displays form the natural 'human-machine interface'. Memory and sensing arrays offer the ability to run parallel read-out and easy multiplexing.

Better materials to improve performance

Now, I would like to turn to the other research direction I mentioned earlier: improving TFT performance. The use of plastic foils limits maximum processing temperatures. We will research mainly organic and amorphous oxide semiconductors that do not require expensive vacuum deposition. We aim to study their electronic properties of single materials, layered stacks and, for organic semiconductors, in (partially) phase-separated mixtures. This complexity – to go beyond a single layer – gives many opportunities to create and optimize device functionality, but also forms a rich and rewarding playground for studying new physical phenomena.

Amorphous oxide semiconductors

Today, one of the most promising candidate technologies is based on indium-gallium-zinc oxide (IGZO), an n-type amorphous metal oxide semiconductor with a mobility around 10 cm^2/Vs. Just 10 years after their discovery by Hosono [17], these semiconductors are used in products such as Apple's iPAD Pro and LG's OLED TVs as they provide smaller, faster and more power-efficient pixel switches. Current products are glass based, and therefore high process temperatures are

not a problem. But one of the key features of IGZO is that it can be deposited by sputtering down to room temperature, making it compatible with plastic substrates. In fact, low-temperature IGZO was used in the display and X-ray detector examples I mentioned earlier. The stability of low-temperature sputtered IGZO is being studied worldwide, and progress is fast. The role of each type of metal cation in IGZO is reasonably well understood [18].

Charge transport in amorphous oxide semiconductors

At a fundamental level, the performance of thin-film electronic devices is governed by charge transport in the semiconductor materials from which they are made.

IGZO can be thought of as a crystalline compound of metal cations and oxide (e.g. InO or ZnO) anions. The ionic bonding configuration means the metal and oxide orbitals are separated, with the empty outer s-orbitals of the metal forming the bottom of the conduction band and the anion's filled p-orbitals the top of the valence band. The band gap is around 3.2 eV, making these materials optically transparent.

For metals, such as indium and gallium, the outer s-orbitals are large enough that adjacent cations overlap. This overlapping structure is shown for a crystalline lattice in Figure 5a and the disordered amorphous state in Figure 5b. These spatially extensive s-state orbitals explain the relatively high carrier mobilities for transparent amorphous oxide semiconductors.

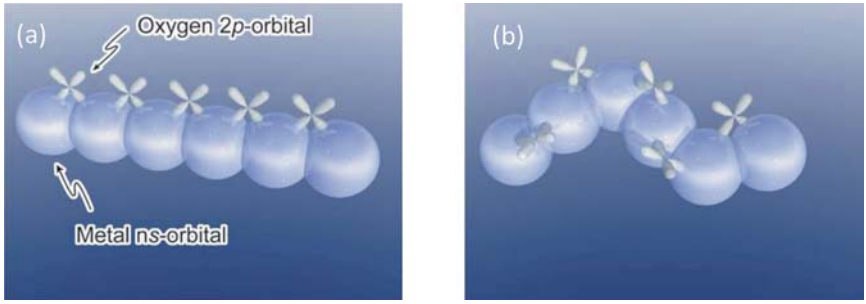

Figure 5

Schematic function of the conduction-band minimum in an oxide crystal (a), which is formed by spatially overlapping metal s orbitals. Even in a disordered structure such as an amorphous oxide (b), the magnitude of the overlap between the neighboring metal cations is not significantly modified. Reproduced from [17,18].

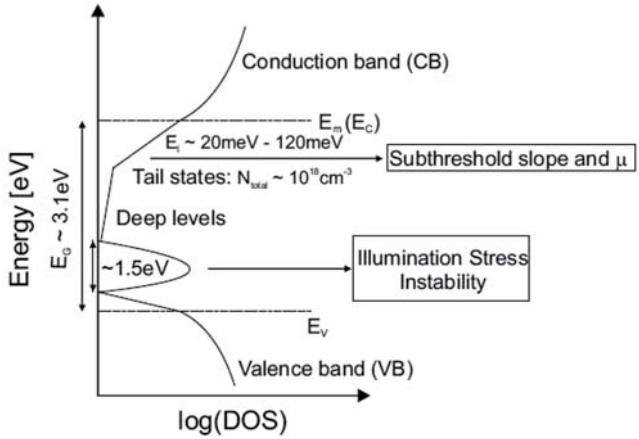

Figure 6

Band structure of IGZO. The exponential band tails stem from the structural disorder in the lattice while the discrete defect bands arise from impurities such as oxygen vacancies and (hydrogen) interstitials. Adopted from [19] by Ajay Bhoolokam [20].

In general, defects plus dynamic and structural disorder are thought to result in tail states below the density of states (DOS) that negatively affect charge transport. How much depends on their energy. If a state is separated from the conduction-band minimum by more than a few k_BT, the state is considered a *deep trap* from which the charge cannot be released by thermal excitation. Conversely, in so-called *shallow trap* states that lie within a few k_BT of the conduction-band minimum, charges can be thermally activated and released into the conduction band or hop to a neighboring site. Figure 6 shows the IGZO band structure and how deep and tail states influence transistor performance.

Investigating these sub-gap states is crucial for a better understanding of fundamental processes that determine operation and the ultimate performance of organic and oxide electronic devices. However, the lack of a proper characterization method has so far hampered research. The temperature dependence of electrical and optical properties can provide valuable information about the electronic band structure, the electronic transitions and electron-phonon interactions.

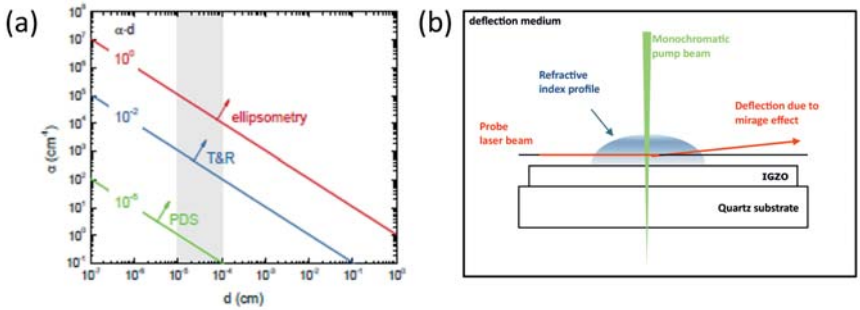

Figure 7

Photothermal deflection spectroscopy can detect tail states in IGZO and other semiconductors. (a) Comparison of the sensitivities of absorption measurements performed with ellipsometry (red), transmission and reflection (blue) and photothermal deflection spectroscopy (green). Applicable film thicknesses range from 100 nm to 1 µm (gray area). (b) Illustration of the mirage effect used to detect optical absorption in a material under test. The absorbed light recombines followed by a warming of the sample, resulting in a temperature gradient and therefore a refractive index gradient in the deflection medium above the sample. Due to the mirage effect a laser beam is deflected away from the surface. (Adopted from D. Krebs thesis 'Electrical Transport and Switching in Phase Change Materials', RWTH Aachen.)

Conventional optical absorption and reflection measurements are not sensitive enough to probe tail states, which typically appear in low concentrations (10^{17} cm^3 or less). Instead, we plan to study these states by combining existing techniques in the group with photothermal deflection spectroscopy (PDS), which is 1000 times more sensitive. Under ideal conditions, this will allow us to measure an absorption of $\alpha = 0.1\ cm^{-1}$ at a film thickness of 1 µm. The method for detecting light absorption is shown in Figure 7B [21]. A sample comprising a thin film of amorphous oxide on a transparent substrate is kept in a liquid transparent deflection medium whose refractive index depends strongly on temperature. Upon exposure to light, the sample heats up, changing the temperature of the deflection medium. The resulting refractive index change can be detected by the deflection of a laser beam passing about 1 µm from the sample's surface.

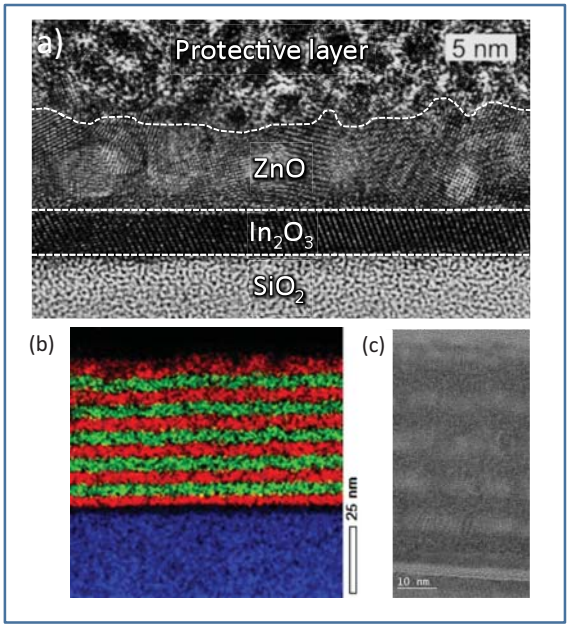

Figure 8

High resolution TEM images of: (a) a solution-processed In_2O_3/ZnO heterostructure [23] and (b+c) alternating ZnO (red) and In_2O_3 layers (green) each about 5 nm thick and deposited using spatial ALD on top of a silicon substrate (blue) [unpublished results Holst Centre/TUe].

New low-dimensional oxide semiconductors

While sputtering is a useful and versatile deposition technique, it requires expensive equipment and plenty of time for each sample to adjust to regular atmospheric conditions. Furthermore, it turns out to be difficult to achieve the right material composition and thickness over large areas, leading to variation in transistor performance particularly for thin films. For that reason, the thickness of the sputtered IGZO films is typically 30 nm or larger.

Hence, we would like to research ways to deposit amorphous oxide semiconductors with the ultimate target of realizing ultra-thin (10 nm or less) films and stacks thereof. Such ultra-thin semiconductors could deliver a step-wise increase in electron mobilities and transistor performance. Let me explain why.

In conventional transistor technologies, electron mobility is limited by the intrinsic properties of the semiconductor material. However, by carefully nano-engineering

low-dimensional heterostructures comprising intrinsic (un-doped) and extrinsic (doped) semiconducting layers, it is possible to overcome the maximum mobility limitation [22]. In the case of GaAs, the electron mobility of the device is enhanced several times by interfacing the GaAs with a larger bandgap material such as AlGaAs. An important feature of these systems is that charge transport is not determined by the bulk properties of the individual oxides, but instead by the electronic properties of the heterointerfaces. In such heterostructures the majority of carriers minimize their energy by diffusing out of one semiconductor layer into other, forming a two-dimensional electron gas (2DEG) close to the heterointerface. The confined carriers exhibit high mobilities which, in many cases, exceed the bulk mobility of the individual semiconductors.

The concept of energy quantization in solution-processed oxide layers is new, but was demonstrated experimentally in 2015 by Anthopoulos et al. [23]. They showed that, in In_2O_3 and ZnO, reducing the semiconductor thickness to such extreme dimensions widens the energy bandgap of the semiconductor compared to its bulk value, in agreement with theoretical predictions [24]. Fig. 8a shows a spray-coated In_2O_3/ZnO heterojunction in cross section. Despite the simplicity of the method, the image reveals a nearly atomically-sharp heterointerface. This and the favorable energetics of the oxides result in electron confinement at the In_2O_3/ZnO interface. The combined effect of energy quantization and electron confinement into discrete energy states is believed to be responsible for the dramatically enhanced electron transport seen in the In_2O_3/ZnO transistors.

Using this preliminary work as a starting point, we will further explore two possibilities for developing complex low-dimensional oxide systems. One approach involves depositing a soluble precursor that is subsequently annealed at high temperature to form a semiconducting metal oxide. The second uses spatial atomic-layer deposition. Figures 8b+c are representative cross-sectional images of In_2O_3/ZnO heterojunctions deposited using spatial atomic layer deposition (ALD). The ZnO layers are crystalline. The In_2O_3 layers are amorphous. Again atomically flat interfaces are achieved. This work will be done in collaboration with Professor Roozeboom of the Plasma & Materials Processing group here and Professor Anthopoulos of Imperial College London in the UK.

Organic transistors

So now I have explained to you how we want to improve oxide semiconductors. But what about the other class of materials that is typically associated with printed and flexible transistors: namely organic semiconductors? In the next part I want to explain to you our plans concerning organic transistors.

Two decades of effort have resulted in impressive improvements in the characteristics of organic TFTs such that, currently, the best organic transistors outperform the widely used amorphous silicon transistors. Single molecular-crystal transistors and polycrystalline films can have mobilities up to 10-20 cm^2/Vs [25]. State-of-the-art polymer field-effect transistors (FETs) reach mobilities up to 10 cm^2/Vs [26]. It has been shown that most, if not all, organic semiconductors are intrinsically capable of conducting electrons as well as holes. [27] Transistors can potentially operate in the electron- and hole-accumulation modes, depending on the polarity of the gate voltage (so-called ambipolar operation). Often, however, ambipolarity is undesirable; the transistor cannot be switched off completely, meaning there will always be a non-negligible leakage current resulting in large power consumption. Electron-conducting organic TFTs are more difficult to realize in practice. For this reason, and the fact that amorphous oxide semiconductors are good n-types, we focus on achieving high hole mobilities in heteroacenes and diketopyrrolopyrrole-type (DPP) polymers.

Previously, we have explored strategies to control the crystallization of heteroacene materials through moving liquid contact lines [28]. High mobility transistors and relatively complex circuits such as 8-bit transponders were inkjet printed [29]. Furthermore, we investigated blends of molecular semiconductors with (insulating) polymers [30].

There are still fundamental questions to help us better understand how high mobilities arise and the correlation between molecular structures and electronic properties. We know charge carrier mobility is governed by molecular structure and resultant morphology but grain size and orientation with respect to the transistor channel plus the exact nature of grain boundaries also play a role. This forms a rich and rewarding playground for fundamental science. For instance, we found that the unexpected field dependence of charge carrier mobility in a pentacene organic FET at low electric fields is a signature of a phenomenon that could be termed as the electric field confinement effect in a grainy organic film. It originates from a lateral redistribution of accumulated (gate-induced) mobile charges by the applied source-drain voltage, at the grain boundaries. It gives rise

to strong local electric field and is relevant for chemically doped organic polycrystalline films and organic films with inhomogeneous morphology caused by, for example, sample annealing to improve charge transport.

For such high mobility devices low contact resistance at the metal-organic semiconductor interface is vital, especially for small channel lengths. This is typically achieved using expensive noble metals such as gold. By inserting specific self-assembled monolayers on the gold injecting contacts, it is possible to suppress charge injection for one charge carrier and (sometimes) enhance the other [31]. Our next step is to replace expensive gold electrodes using specific doped organic intermediate layers. While doping a guest molecule into a host molecule has been extensively studied for increasing conductivity to reduce voltage drops within OLEDs and OPVs (electrical doping), these methods must be modified to be applicable to TFTs. We will study the doping mechanism in detail using the previously mentioned photothermal deflection spectroscopy.

Alternatively, it is also possible to electrostatically switch a transistor from ambipolar to unipolar (either n- or p-type) with large on-off currents using a tri-gate transistor structure. [32] Such structures allow independent control of charge injection at the source and drain contacts as well as charge transport in the semiconductor. The polarity of the transistor is not permanent: when the voltage is removed the transistor switches back to its original position. This enables easy integration in low-power complementary circuits as well as volatile electronic memories.

Functional dielectric: memories, actuators and sensors

One area that has attracted particular attention is the development of multi-functional thin-film devices combining two or more types of physical properties in a single device. TFT-based sensors, light-emitting transistors, photodetectors and memory cells have all been demonstrated. Solution processing and self-assembly provide a unique route to conceptually novel approaches for information storage and sensors. We will investigate the (relaxor) ferroelectric , piezoelectric, pyroelectric and properties of co-polymers of vinylidene fluoride (VDF) and trifluoroethylene (TrFE) [P(VDF-TrFE)] in thin-film transistors and diodes (Figure 9).

P(VDF-TrFE) exhibits a large spontaneous polarization of 0.05-0.1 C/m^2, excellent polarization stability and high electrical resistivity up to 10^{12} Ωcm with switching times as short as 0.1 ms. P(VDF-TrFE) can possess spontaneous electric fields that are more than an order of magnitude larger than the breakdown field of SiO_2,

a commonly used dielectric in field effect devices. The use of the ferroelectric polarization field thus allows extremely large modulation of the charge carrier density in transistor channels and non-volatile memories. Moreover, its piezoelectric properties can be exploited in ultrasound actuators and pressure sensors.

Ferro electric • Memory/data storage	**High-k dielectric** • Low-voltage TFTs
Piezo electric/relaxor • Actuators • Sensors	**Pyro electric** • Temperature sensors

Figure 9

Overview of properties and applications of P(VDF)-based dielectrics.

Open innovation

Clearly then, there are many profitable avenues of research still to be explored. And research is teamwork. If you haven't already read it, I strongly recommend Isaacson's book *The Innovators* in which he convincingly shows that groups of people working together can achieve amazing things. We all know breakthroughs are often found where disciplines intersect. This calls for collaboration. Collaboration between researchers, research teams and different research organizations. Nowadays this is called open innovation or shared research, but in fact research collaboration dates back to the days of Edison. Edison was the first to forge industrially relevant applied research, by managing teams of researchers who could experiment on all aspects of his inventions and moving them rapidly from research to development and commercialization. In Eindhoven, Dr. Gilles Holst founded Philips Research Laboratories along the same principles in 1914. Almost one hundred years later, his name was attached to a new research institute in the Netherlands: Holst Centre.

Holst Centre was established in 2005 as a partnership between academia, industry and government to collaborate on the development of a new generation of flexible and wearable electronics. Part of Holst Centre's success comes from strong collaborations with several academic groups worldwide. This interaction fuels the Centre with deeper understanding and new ideas. Holst Centre's turns the know-how and ideas into viable technologies that are then commercially exploited by partner companies. This eco-system works so well because all parties have a clear and distinct role, a prerequisite for efficient and effective collaboration.

By establishing this chair we can intensify the already strong relationship between Holst Centre and the University of Eindhoven. The chair is embedded in the Molecular Materials and Nanosystems (M2N) group, which combines making new materials and detailed investigations of charge transport mechanisms and photophysics with fabrication, characterization and modeling of prototype devices. I hope I have shown good examples of this. By initiating academic

research projects with PhD and MSc students on topics in line with Holst Centre's strategic directions, I will ensure that the research of this chair has impact in both education and industry. After graduation, these students will provide valuable knowledge for academia, local industry and Holst Centre itself.

Acknowledgments

I am very aware that I am in a unique position at the interface of several scientific disciplines, between a university and a company, and between creativity and analysis. And for that, I am very grateful to a number of people.

It is an honor to be part of this university. So I would like to thank Gerrit Kroesen for giving me the opportunity to establish the research chair in the department of Applied Physics. Special thanks also to Rene Janssen for his enthusiasm in jointly undertaking this endeavor. Rene, thanks! I also want to thank the other members of the Molecular Materials and Nanosystems group. I enjoy the lively discussions with students and colleagues on Friday mornings.

Working beyond the boundaries of my own field with talented people from other departments and universities has always been a source of inspiration. I want to mention here Eugenio Cantatore in the Electronic Engineering Department who really enjoys designing circuits even though the technology is not always predictable. I also want to mention Fred Roozeboom of the Plasma group. Together we have great visions of what atmospheric atomic layer deposition can do for flexible electronics. Let's continue the collaboration.

My university role is part-time. In parallel, I'm a scientist and program director at Holst Centre, which aims to bring new technologies to market. This requires collaborations between experts in technology, applications and business. I feel privileged to participate in such a process, and want to thank Ton van Mol, Jaap Lombaers and Peter Werkhoven: managers who have supported me in combining my main job with a part-time professorship at TU/e.

In the past decade, I have had the honor of working with excellent scientists, technologists and technicians from very diverse disciplines on a large variety of topics in a dynamic environment. There couldn't have been a better environment for my personal growth and development. My deepest gratitude goes to all the great people working at Holst Centre, and especially the Organic and Oxide Transistors team. I wouldn't be standing here today if not for the amazing job you all do every day. I want to give special thanks to Paul Blom and Paul Heremans,

who taught me the importance of combining scientific excellence with industrially-relevant R&D. I also thank Holst Centre's industrial partners for fruitful collaborations. Their multi-year commitment has been instrumental in the progress that we are jointly making.

Finally, I want to thank my family and friends for their years of support. Audrey, thank you for your love and presence, and for the joy of jointly taking care of Nienke, Jelle and Max. I want to thank my parents who always encouraged me to educate myself.

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References

1. Source: Daniel Forster, Applied Materials. Sources of information: SIA, IC Knowledge LLC; Display Search, Nikkei BP, Applied Materials, Photon Consulting 2012.
2. J.P. Morgan Markets, “Electronic Components Update,” 2014.
3. H.E.A. Huitema, G.H. Gelinck, J.B.P.H. van der Putten, K.E. Kuijk, C.M. Hart, E. Cantatore, P.T. Herwig, A.J.J.M. van Breemen, D.M. de Leeuw, Plastic transistors in active-matrix displays, Nature (London), 414 (2001) 599; G.H. Gelinck, H.E.A. Huitema, E. van Veenendaal, E. Cantatore, L.R.R. Schrijnemakers, J.B.P.H. van der Putten, T.C.T. Geuns, M.J. Beenhakkers, J.B. Giesbers, B.H. Huisman, E.J. Meijer, M.E. Mena Benito, F.J. Touwslager, A.W. Marsman, B.J.E. van Rens, D.M. de Leeuw, Flexible active-matrix displays and shift registers based on solution-processed organic transistors, Nature Materials, 3 (2004) 106-110.
4. Gerwin H. Gelinck, Abhishek Kumar, Date Moet, Jan-Laurens van der Steen, Umar Shafique, Pawel E. Malinowski, Kris Myny, Barry P. Rand, Matthias Simon, Walter Ruetten, Alexander Douglas, Jorrit Jorritsma, Paul Heremans, Ronn Andriessen, X-ray imager using solution processed organic transistor arrays and bulk heterojunction photodiodes on thin, flexible plastic substrate, Organic Electronics, 14 (2013) 2602-2609.
5. Gerwin H. Gelinck, Abhishek Kumar, Date Moet, Jan-Laurens van der Steen, Albert J.J.M. van Breemen, Santosh Shanmugam, Arjan Langen, Jan Gilot, Pim Groen, Ronn Andriessen, Matthias Simon, Walter Ruetten, Alexander U. Douglas, Rob Raaijmakers, Pawel E. Malinowski, Kris Myny, X-ray detector on plastic with high sensitivity using low cost, solution-processed organic photodiodes, IEEE Transactions Electron Devices 10.1109/TED.2015.2432572.
6. E. Cantatore, T.C.T. Geuns, G.H. Gelinck, E. van Veenendaal, A.F.A. Gruijthuijsen S. Drews, D.M. de Leeuw, A 13.56-MHz RFID System Based on Organic Transponders, IEEE J. Solid-State Circuits, 42 (2007) 84-92; A.K. Tripathi, E.C.P Smits, J.B.P.H. van der Putten, M. van Neer, K. Myny, M. Nag, S. Steudel, P. Vicca, K. O’Neill, E. van Veenendaal, J. Genoe, P. Heremans, and G.H. Gelinck, Low-voltage gallium-indium-zinc-oxide thin film transistors based logic circuits on thin plastic foil: Building blocks for radio frequency identification application, Appl. Phys. Lett., 98 (2011) 162102.
7. Kris Myny, Steve Smout, Maarten Rockelé, Ajay Bhoolokam, Tung Huei Ke, Soeren Steudel, Brian Cobb, Aashini Gulati, Francisco Gonzalez Rodriguez, Koji Obata, Marko Marinkovic, Duy-Vu Pham, Arne Hoppe, Gerwin H. Gelinck, Jan Genoe, Wim Dehaene, and Paul Heremans, ‘Microprocessors on everything: a thin-film computer with inkjet

print-programmable memory', Scientific Reports, 4 (2014) 7398 doi:10.1038/srep07398.
8. D.-H. Kim, Y.-S. Kim, J. Wu, Z. Liu, J. Song, H.-S. Kim, Y.Y. Huang, K.-C. Hwang, J.A. Rogers, Adv. Mater. 2009, 21, 3703;DOI: 10.1002/adma.200900405.
9. H. Fuketa, K. Yoshioka, Y. Shinozuka, K. Ishida, T. Yokota, N. Matsuhisa, Y. Inoue, M. Sekino, T. Sekitani, M. Takamiya, T. Someya, T. Sakurai, IEEE Trans. Biomedical Circuits and Systems, 2014, 8, 824; DOI:10.1109/TBCAS.2014.2314135; H. Fuketa, K. Yoshioka, Y. Shinozuka, K. Ishida, T. Yokota, N. Matsuhisa, Y. Inoue, M. Sekino, T. Sekitani, M. Takamiya, T. Someya, T. Sakurai, IEEE ISSCC Digest of Technical Papers, 2013, 104.
10. Tomoyuki Yokota, Yusuke Inoue, Yuki Terakawa, Jonathan Reeder, Martin Kaltenbrunner, Taylor Ware, Kejia Yang, Kunihiko Mabuchi, Tomohiro Murakawa, Masaki Sekino, Walter Voit, Tsuyoshi Sekitani, and Takao Someya, Ultraflexible, large-area, physiological temperature sensors for multipoint measurements, Proc Natl Acad Sci U S A. 2015 Nov 24;112(47):14533-8. doi: 10.1073/pnas.1515650112.
11. Paul Heremans, Ashutosh K. Tripathi, Albert de Jamblinne de Meux, Bo Hou, Geoffrey Pourtois, Edsger C.P. Smits, Gerwin H. Gelinck, Mechanical and electronic properties of thin-film transistors on plastic, and their integration in flexible electronic applications, Adv. Materials, in press.
12. http://www.stw.nl/nl/content/large-area-smart-pressure-sensors-foil-smart-press
13. T. Guenther, N.H. Lovell, G.J. Suaning, Expert Rev. Med. Device, 9, 33-48 (2012).
14. K. Mathieson, J. Loudin, G. Goetz, P. Huie, L. Wang, T.I. Kamins, L. Galambos, R. Smith, J.S. Harris, A. Sher, D. Palanker, 'Photovoltaic retinal prosthesis with high pixel density', Nature Photonics, 6, 391 (2012).
15. J. Dowling, Eye, 22, 1-7 (2008).
16. Diego Ghezzi, Maria Rosa Antognazza, Marco Dal Maschio, Erica Lanzarini, Fabio Benfenati, and Guglielmo Lanzani, A hybrid bioorganic interface for neuronal photoactivation, Nature Communications, 2 (2010) 166(doi:10.1038/ncomms1164).
17. Kenji Nomura, Hiromichi Ohta, Akihiro Takagi, Toshio Kamiya, Masahiro Hirano, and Hideo Hosono, Room-temperature fabrication of transparent flexible thin-film transistors using amorphous oxide semiconductors, Nature 432, (2004) 488-492.
18. Toshio Kamiya and Masashi Kawasaki, ZnO-Based Semiconductors as Building Blocks for Active Devices, MRS Bulletin, 33 (2008) 1061-1066.
19. Toshio Kamiya, Kenji Nomura, and Hideo Hosono, Origins of High Mobility and Low Operation Voltage of Amorphous Oxide TFTs: Electronic Structure, Electron Transport, Defects and Doping, J. Display Technology 5 (2009) 468-483.
20. Ajay Bhoolokam, Ph.D thesis 'Characterization of amorphous Indium Gallium Zinc Oxide thin film transistors', KU Leuven.
21. W.B. Jackson, N.M. Amer, A.C. Boccara, and D. Fournier. Photothermal Deflection Spectroscopy and Detection. Applied Optics, 20(8) (1981)1333-1344.
22. H. Kroemer, Nobel Lecture: Quasielectric fields and band offsets: teaching electrons new tricks, Rev. Modern Physics, 73 (2001) 783-793; Z.I. Alferov, Nobel Lecture:

The double heterostructure concept and its applications in physics, electronics, and technology, Rev. Modern Physics, 73 (2001) 767-782.

23. John G. Labram, Yen-Hung Lin, Kui Zhao, Ruipeng Li, Stuart R. Thomas, James Semple, Maria Androulidaki, Lamprini Sygellou, Martyn McLachlan, Emmanuel Stratakis, Aram Amassian, Thomas D. Anthopoulos, Signatures of Quantized Energy States in Solution-Processed Ultrathin Layers of Metal-Oxide Semiconductors and Their Devices, Advanced Functional Materials 25, (2015) 1727.
24. Yen-Hung Lin, Hendrik Faber, John G. Labram, Emmanuel Stratakis, Labrini Sygellou, Emmanuel Kymakis, Nikolaos A. Hastas, Ruipeng Li, Kui Zhao, Aram Amassian, Neil D. Treat, Martyn McLachlan, and Thomas D. Anthopoulos, High Electron Mobility Thin-Film Transistors Based on Solution-Processed Semiconducting Metal Oxide Heterojunctions and Quasi-Superlattices, Adv. Science, 2 (2015), 1500058.
25. Huanli Dong, Xiaolong Fu, Jie Liu, Zongrui Wang, and Wenping Hu, Key Points for High-Mobility Organic Field-Effect Transistors, Adv. Mater. 2013, 25, 6158-6183.
26. C.B. Nielsen, M. Turbiez, I. McCulloch, Adv. Mat., 2013, 25, 1859; DOI: 10.1002/adma.201201795.
27. L.-L. Chua, J. Zaumseil, J.-F. Chang, E.C.-W. Ou, P.K.-H. Ho, H. Sirringhaus, R.H. Friend, Nature 2005, 434, 194.
28. Christoph Sele, Charlotte Kjellander, Björn Niesen, Martin Thornton, Bas van der Putten, Kris Myny, Harry Wondergem, Armin Moser, Roland Resel, Albert van Breemen, Nick van Aerle, Paul Heremans, John Anthony and Gerwin Gelinck, Controlled deposition of highly ordered soluble acene thin films: effect of morphology and crystal orientation on transistor performance, Adv. Mater. 21, (2009) 4926-4931.
29. B.K. Charlotte Kjellander, Wiljan T.T. Smaal, Kris Myny, Jan Genoe, Wim Dehaene, Paul Heremans, Gerwin H. Gelinck, Optimized circuit design for flexible 8-bit RFID transponders with active layer of ink-jet printed small molecule semiconductors, Organic Electronics, 14 (2013) 768-774.
30. Xiaoran Li, Wiljan T.T. Smaal, Charlotte Kjellander, Bas van der Putten, Kevin Gualandris, Edsger C.P. Smits, John Anthony, Dirk J. Broer, Paul W.M. Blom, Jan Genoe, Gerwin Gelinck, Charge transport in high-performance ink-jet printed single-droplet organic transistors based on a silylethynyl substituted pentacene/insulating polymer blend, Organic Electronics 12 (2011) 1319-1327.
31. Wiljan Smaal, Charlotte Kjellander, Yongbin Jeong, Ashutosh Tripathi, Bas van der Putten, Antonio Facchetti, Henry Yan, Jordan Quinn, John Anthony, Kris Myny, Wim Dehaenee, Gerwin Gelinck, Complementary integrated circuits on plastic foil using inkjet printed n- and p-type organic semiconductors: Fabrication, characterization, and circuit analysis, Organic Electronics, 13 (2012) 1686-1692.
32. Fabrizio Torricelli, Matteo Ghittorelli, Edsger C.P. Smits, Christian W.S. Roelofs, René A.J. Janssen, Gerwin H. Gelinck, Zsolt M. Kovács-Vajna, Eugenio Cantatore, Ambipolar Organic Tri-Gate Transistor for Low-Power Complementary Electronics, in press (DOI: 10.1002/adma.201503414).

Curriculum Vitae

Prof.dr. Gerwin Gelinck was appointed part-time professor of Flexible, Large-Area Electronics in the Department of Applied Physics at Eindhoven University of Technology (TU/e) on September 1, 2014.

Gerwin Gelinck received his Master of Science degree in Chemistry at the University of Nijmegen and his PhD degree from the Delft University of Technology, in 1998. In that same year he joined Philips Research as Senior Scientist. In 2002 he was co-founder of Polymer Vision, an internal startup company in the Philips Technology Incubator. From 2002 to 2006 he was Chief Scientist of Polymer Vision. Since 2007 he has been working at Holst Centre/TNO, first as Program Manager and since 2015 as Program Director. He became part-time professor at Eindhoven University of Technology in 2014. Also in 2014 he became Principal Scientist at TNO. His current research interests include flexible transistors and their applications (displays, imagers), organic photodetectors, polymer actuators and ferroelectric memories.

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