POx/Al2O3 stacks for surface passivation of Si and InP

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PO\textsubscript{x}/Al\textsubscript{2}O\textsubscript{3} stacks for surface passivation of Si and InP

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\section*{Abstract}

Passivation of semiconductor surfaces is crucial to reduce carrier recombination losses and thereby enhance the device performance of solar cells and other semiconductor devices. Thin-film stacks of phosphorus oxide (PO\textsubscript{x}) and aluminum oxide (Al\textsubscript{2}O\textsubscript{3}) have recently been shown to provide excellent passivation of semiconductor surfaces, including crystalline silicon and indium phosphide, and can also be highly interesting for passivation of other semiconductor materials such as Ge and III-V semiconductors. On silicon, the excellent passivation is attributed to the combination of a high positive fixed charge and a very low interface defect density. On InP nanowires, application of the PO\textsubscript{x}/Al\textsubscript{2}O\textsubscript{3} layers improves charge carrier lifetime threefold as compared to unpassivated nanowires. In this work, we review and summarize recent results obtained on PO\textsubscript{x}/Al\textsubscript{2}O\textsubscript{3} stacks for semiconductor surface passivation. Several topics are discussed, including the passivation performance on various semiconductor surfaces, the processing of the PO\textsubscript{x} and Al\textsubscript{2}O\textsubscript{3} layers, the role of the capping layer, and aspects related to device integration. The PO\textsubscript{x}/Al\textsubscript{2}O\textsubscript{3} stacks feature some unique properties, including an unusually high positive fixed charge density, a low interface defect density, and can be prepared over a wide deposition temperature range. These unique properties arise in part from the mixing process that occurs between the PO\textsubscript{x} and Al\textsubscript{2}O\textsubscript{3} layers, which upon post-deposition annealing leads to the formation of AlPO\textsubscript{4}. The surface passivation provided by PO\textsubscript{x}/Al\textsubscript{2}O\textsubscript{3} stacks is highly stable and the stack can be used to conformally coat high-aspect-ratio structures such as nanowires, showing their promise for use in semiconductor devices.

\section{1. Introduction}

Semiconductor materials form the basis for many electronic and optoelectronic devices, such as transistors, lasers, photodetectors, power devices, light emitting diodes (LEDs), and solar cells [1]. Silicon has been of great importance in these applications and has been the dominant material for micro-electronics [2] and photovoltaics [3]. However, alternatives to silicon have also been extensively investigated, including germanium and III-V compound semiconductors. Group III-V semiconductors have shown some advantages over silicon, mainly because of their direct bandgap and high electron mobilities [4]. Germanium also has a higher carrier mobility than Si [5], and hexagonal Ge and SiGe alloys were reported to have direct bandgaps [6]. The direct bandgap allows for optoelectronic applications such as LEDs [7,8] and lasers [9, 10]. Furthermore, the high carrier mobilities make these semiconductors interesting alternatives to silicon for certain applications, such as field-effect transistors (FETs) [5,11,12]. Germanium specifically is relevant for complementary metal-oxide-semiconductor (CMOS) applications, because it has both a high electron mobility, as well as a high hole mobility [5,13]. These alternative semiconductors are sometimes combined with silicon, which has a very mature processing technology. Examples are Ge on Si [10,14–18] and III-V on Si [8,9,19] technologies, which are used for photonic applications.

Recombination at surfaces of Si, Ge, and III-V semiconductors due to (surface) defect states can significantly limit device performance. For silicon, this is exemplified by silicon solar cells, where initial performance was limited by defects in the silicon bulk. However, as the Si bulk material quality kept improving, recombination processes at the surface...
became dominant [20]. For the use of germanium in field effect transistors, achieving a high quality interface between the Ge and the high-k dielectric is a major challenge [13]. For III-V semiconductors, such as GaAs, InP, InGaAs, InSb, and GaN, recombination processes at the surface also significantly reduce device performance [21,22]. Proper surface passivation is therefore critical to reduce the number of defects at the surface, which are generally expressed in terms of the interface defect density \(D_i\). Reduction of the \(D_i\) leads to a reduction of Shockley–Read–Hall (SRH) recombination enabled by these defects. Proper surface passivation becomes even more crucial with further device downscaling and the emergence of highly structured nanodevices, which typically have higher surface-to-volume ratio. This leads to surface recombination processes becoming even more dominant.

Although Ge and III-V semiconductors exhibit some advantageous properties compared to silicon, in terms of surface passivation these materials face their own specific challenges. The oxide of silicon (SiO\(_2\)) is straightforward to obtain and provides excellent surface passivation of silicon surfaces [23], which is mainly enabled by a very low \(D_i\) of SiO\(_2\) on Si and is one of the reasons why silicon has become the dominant semiconductor in electronic applications. In contrast, passivation of germanium by its oxide (GeO\(_2\)) is challenging, because it is unstable at elevated temperatures and soluble in water [24–27]. For III-V semiconductors, passivation by their oxides is also challenging, as they generally result in poor interface quality [28]. Therefore, germanium and III-V semiconductors typically require surface passivation by materials other than their oxides and even for surface passivation of silicon, there is a demand of alternative layers with additional features beside a low \(D_i\). For FETs for example, a high-k value of the dielectric is desired [29]. For solar cells, a high fixed charge (\(Q_f\)) contained within the passivation layer or at the surface of the semiconductor can be desirable [23], or the passivation layer should be able to conduct charge, i.e. act as passivating contact [30]. These requirements have led researchers to consider different materials for surface passivation of Si, Ge, and III-V semiconductors, including a-Si:H, Al\(_2\)O\(_3\), SiN\(_x\), SiO\(_2\), TiO\(_2\), Ga\(_2\)O\(_3\), HfO\(_2\), AlN, Ta\(_2\)O\(_5\), ZrO\(_2\), ZnO, Nb\(_2\)O\(_5\), or stacks thereof [23,29,31–44], which have led to varying degrees of surface passivation. Continued research on surface passivation of these semiconductors is key to allow further device scaling, to enable devices based on a wider variety of semiconductor substrate materials, and finally to improve device performance.

Recently, a novel stack of phosphorus oxide and aluminum oxide (PO\(_x\)/Al\(_2\)O\(_3\)) has been shown to provide excellent surface passivation of both Si [45–48] and InP [49] surfaces. On silicon, the PO\(_x\)/Al\(_2\)O\(_3\) stacks have been shown to achieve a very low \(D_i\) on the order of 10\(^{10}\) cm\(^{-2}\) s\(^{-1}\) at a high fixed positive charge density (\(Q_f\)) on the order of 10\(^{12}\)–10\(^{13}\) cm\(^{-2}\). On planar InP and InP nanowires, it has been shown that PO\(_x\)/Al\(_2\)O\(_3\) stacks improve the charge carrier lifetime and thermal stability of the InP. The PO\(_x\)/Al\(_2\)O\(_3\) stacks therefore show great promise as passivation scheme for both Si and InP semiconductor devices, and in particular for solar cell devices. It has furthermore been shown that the PO\(_x\)/Al\(_2\)O\(_3\) stack provides state-of-the-art passivation on textured n\(^+\)-doped Si, which is frequently used on the front side of c-Si solar cells [48] and recently InP nanowire solar cells with extremely low material consumption featuring the PO\(_x\)/Al\(_2\)O\(_3\) stack as passivation scheme have been realized [50]. The PO\(_x\)/Al\(_2\)O\(_3\) stacks may also prove to be beneficial as passivation layer on other III-V semiconductors or germanium.

Here, we review the recent results obtained on surface passivation by PO\(_x\)/Al\(_2\)O\(_3\) stacks. First, in Section 2, the material and semiconductor surfaces are discussed, specifically for Si and InP, whereon the PO\(_x\)/Al\(_2\)O\(_3\) stack has been shown to achieve excellent surface passivation. This is followed in Section 3 by a discussion on the processing steps required to obtain PO\(_x\)/Al\(_2\)O\(_3\) stacks, in particular for two different deposition processes, i.e. plasma-enhanced atomic layer deposition (PE-ALD) and pulsed-flow plasma-enhanced chemical vapor deposition (PF-PECVD). In Section 4, the role of the Al\(_2\)O\(_3\) capping layer is discussed, which is shown to have a significant effect on the passivation quality provided by the PO\(_x\)/Al\(_2\)O\(_3\) stack and to mix with the PO\(_x\) layer, leading to structural changes upon annealing. Lastly, in Section 5, aspects pertaining to device integration are discussed, in particular conformity and stability.

2. Passivation of semiconductor surfaces

2.1. Passivation of InP and Si

PO\(_x\)/Al\(_2\)O\(_3\) stacks for semiconductor passivation have first been reported on InP surfaces [49]. InP surfaces are highly sensitive to heat treatments [51,52]. Desorption of P from the InP can occur at temperatures higher than 200 °C in vacuum [53], which can result in phosphorus-vacancy-related defects. Therefore, low-temperature processes are required for passivation of InP surfaces [54]. Desorption of P from the InP surface might be reduced by using a P-rich passivation layer, which has led to the consideration of a layer of PO\(_x\) for passivation of InP surfaces. We note that this PO\(_x\) layer is different from the native oxide of InP, which is a mix of indium oxide and phosphorus oxide. However, PO\(_x\) is highly hygroscopic [55] and degrades within minutes in air, turning into phosphoric acid. To avoid such degradation, Al\(_2\)O\(_3\) has been used as a capping layer to protect the PO\(_x\) layer from reactions with the ambient, resulting in the PO\(_x\)/Al\(_2\)O\(_3\) stack.

On planar InP and InP nanowires (NW), it has been shown that stacks of PO\(_x\)/Al\(_2\)O\(_3\) deposited at low temperature (25 °C) result in an increase in carrier lifetime and an increase in thermal stability of the InP [49]. The carrier lifetime was increased by a factor of 3 compared to an unpassivated InP NW (where notably the bare InP surface is considered to already be relatively well-passivated) due to the surface passivation provided by the PO\(_x\)/Al\(_2\)O\(_3\) stacks. On the other hand, deposition of only an Al\(_2\)O\(_3\) layer was found to lead to degradation of the InP NW, demonstrating the importance of the PO\(_x\) layer and showing the potential of PO\(_x\)/Al\(_2\)O\(_3\) stacks for InP surface passivation. Following the good results obtained on passivation of InP surfaces, the PO\(_x\)/Al\(_2\)O\(_3\) stacks were investigated for the passivation of silicon surfaces. On silicon, the PO\(_x\)/Al\(_2\)O\(_3\) stacks [45] provide surface passivation on the same level as Al\(_2\)O\(_3\), which is well-known to be a highly effective passivation layer [31].

The surface passivation provided by PO\(_x\)/Al\(_2\)O\(_3\) stacks on Si and InP NWs is summarized in Fig. 1, where the carrier lifetime is plotted as a function of the post-deposition annealing temperature. Carrier lifetimes determined on the unpassivated surfaces and surfaces passivated by Al\(_2\)O\(_3\) are also plotted for comparison. Annealing is required to activate the surface passivation, which is the case for both Si and InP, although lower annealing temperatures are required for InP. The effect of annealing on PO\(_x\)/Al\(_2\)O\(_3\) stacks will be discussed further in section 3.1.4 and 4.2.

The carrier lifetimes determined on Si and InP shown in Fig. 1 vary by several orders of magnitude. This is related to a difference in the predominant recombination mechanism [56]. For silicon this is SRH recombination, except at high injection levels, where Auger recombination starts to dominate. For InP and other direct-bandgap materials, assuming high-quality material, the dominant recombination mechanism is radiative recombination. Due to these differences in recombination mechanism, different characterization techniques are used to determine the carrier lifetimes on Si and on III-V materials. For silicon, the carrier lifetimes are often determined by photoconductance decay (PCD) measurements [57], which typically result in carrier lifetimes on the order of microseconds to milliseconds [23]. For III-V materials, time-resolved photoluminescence (TRPL) is frequently used [58], which typically results in carrier lifetimes on the order of picoseconds to nanoseconds [59–61].

2.2. Impact of deposition process on surface passivation quality

After the first report of excellent passivation on c-Si [45], the surface passivation quality of PO\(_x\)/Al\(_2\)O\(_3\) stacks on c-Si was investigated in more
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Fig. 1. Carrier lifetimes of Al₂O₃- and POₓ/Al₂O₃-passivated planar 280 μm thick, 1–5 μcm, n-type FZ Si (100) wafers (data points with solid lines) and wurtzite InP nanowires (data points with dashed lines), as a function of annealing temperature (10 min in N₂), together with unpassivated semiconductor surfaces as reference. The first data points represent the as-deposited or as-received passivation quality. Data on InP nanowires were adapted from Black et al. [49] Note that the reported carrier lifetimes on Si were determined using photoconductance decay, while the carrier lifetimes on InP NWs were determined using time-resolved photoluminescence.

detail. Initial works employed plasma-enhanced atomic layer deposition (PE-ALD) to deposit the POₓ/Al₂O₃ stacks [45,46]. In later works, the POₓ layer was deposited by a pulsed-flow plasma-enhanced chemical vapor deposition (PF-PECVD) process instead [47,48,62]. The details of these deposition processes will be discussed in section 3.1. The passivation provided by the POₓ/Al₂O₃ stacks resulted in high minority carrier lifetimes, i.e. high passivation quality on silicon over a wide range of deposition temperatures, regardless of the deposition process used, as shown in Fig. 2a. These high lifetimes are enabled by the unique combination of a very low interface defect density (Dₓ) and a high positive fixed charge density (Qₓ), as shown in Fig. 2b and c, respectively. The interface defect density is a measure for the chemical passivation provided by the passivation layer, where lower is better. On the other hand, fixed charge can aid in surface passivation due to modification of the surface carrier concentrations, which can reduce recombination. This is generally referred to as field-effect passivation [23].

The Dₓ value corresponding to the layer stack fabricated by the PF-PECVD process for the POₓ layer, is influenced by deposition temperature, resulting in an increase in Dₓ at higher deposition temperatures. Interestingly, an increase in deposition temperature for the PE-ALD process from 100 °C to 200 °C did not result in an increase in Dₓ, although the exact mechanism is not known. The Qₓ value is not significantly affected by the deposition temperature nor the deposition technique, and a high positive Qₓ on the order of 10¹²–10¹³ cm⁻² is obtained in all cases. The processing of POₓ/Al₂O₃ stacks appears to be quite robust, as over a wide range of deposition temperatures and using different types of deposition processes, a high passivation quality can be obtained.

2.3. Overview of Dₓ and Qₓ

Fig. 2 presents an overview of interface properties of passivation schemes on c-Si, which puts the Dₓ and Qₓ values of the POₓ/Al₂O₃ stacks in perspective with other passivation schemes. In Fig. 2a, the defect density is plotted, which generally ranges from 10¹⁰ to 10¹⁵ eV⁻¹ cm⁻². The POₓ/Al₂O₃ stacks reach very low Dₓ values, on a level similar to Al₂O₃ and SiOₓ, and lower than SiNx. Hydrogenated amorphous silicon (a-Si:H) reaches even lower values for Dₓ. Note that the Dₓ values of a-Si:H are not direct experimental measurements but result from modeling of lifetime data under certain assumptions. It is well known that a-Si:H provides excellent chemical passivation of c-Si [30,63,64], which has enabled for example the world-record efficiency of 26.6% for single-junction silicon solar cells [65,66]. However, these a-Si:H layers also result in parasitic optical absorption losses and are not very thermally stable [30].

In c-Si solar cells, Al₂O₃ is commonly used as passivation layer on p-type Si surfaces, while SiNx (or a SiOₓ/SiNx stack) is frequently used on n-type surfaces [67], in part due to their high negative and positive fixed charge on silicon, respectively. Fig. 2b depicts the fixed charge of different passivation schemes on silicon. The POₓ/Al₂O₃ stacks show a very high positive fixed charge on silicon, on the order of 10¹²–10¹³ cm⁻². This is higher than the positive fixed charge provided by SiNx, and similar to the magnitude of the negative fixed charge provided by Al₂O₃. Due to this unique combination of high positive fixed charge, combined with the very low Dₓ, POₓ/Al₂O₃ stacks have been shown to be highly effective for the passivation of highly doped n-type Si surfaces, which are frequently used in silicon solar cells. It has been found that the passivation provided by POₓ/Al₂O₃ on n⁺-doped silicon rivals state-of-the-art ‘alnealed’ SiO₂ and SiOₓ/SiNx/SiOₓ (ONO) stacks, and results in higher passivation quality than that provided by SiNx and SiOₓ/SiNx stacks [48].

The origin of the low Dₓ enabled by POₓ/Al₂O₃ on silicon is found to be related to surface passivation provided by hydrogen and the formation of AlPOₓ upon annealing, leading to a decrease in Dₓ by almost 3 orders of magnitude from ~10¹⁵ to ~10¹⁰ eV⁻¹ cm⁻² [47]. On silicon a
high positive fixed charge of around $10^{12}$-$10^{13}$ cm$^{-2}$ is present, both after deposition and after annealing [47]. On InP NWs, PO$_x$/Al$_2$O$_3$ stacks induce an n-type field-effect, which indicates the presence of positive fixed charges [95]. The origin of the high positive fixed charge, however, has not been established. It is suggested that the [(O-)P]$^+$ defect (P bonded to four bridging oxygen atoms) can be a likely origin for the positive fixed charge of the PO$_x$/Al$_2$O$_3$ stacks [43]. This defect is structurally analogous to [(O-)Al], which has been proposed as the origin of negative fixed charge in Al$_2$O$_3$ [96]. The high positive fixed charge density is already present in the as-deposited state. Upon annealing, AlPO$_4$ is formed mainly in the PO$_x$ layer (see section 4.2), but the positive fixed charge density does not change [47]. This suggests that the mixing of the Al into the PO$_x$ layer does not significantly affect the fixed charge, possibly because the fixed charges are situated near the silicon interface.

3. PO$_x$/Al$_2$O$_3$ processing

3.1. Process flow

Fig. 4 schematically shows a typical process flow of the fabrication of PO$_x$/Al$_2$O$_3$ stacks. The substrates used so far are Si and InP, but other substrates such as germanium or III-V semiconductors may also be used. First, an optional surface pre-treatment can be used, for example to remove the thin (native) oxide layers from the substrate prior to deposition. Then, the PO$_x$ layer and Al$_2$O$_3$ layers are deposited, where it is important that deposition of the Al$_2$O$_3$ capping layer is performed in-situ to avoid degradation of the PO$_x$ layer upon exposure to the ambient. Finally, a post-deposition annealing treatment is used, which has been found to be required to activate the passivation. In this section, these processing steps will be discussed in more detail.

3.1.1. Pre-treatment

The surface can receive a pre-treatment prior to deposition of the PO$_x$ and Al$_2$O$_3$ stacks. A common pre-treatment is the removal of the surface oxides, for example using a short exposure to dilute hydrofluoric acid, also known as an HF dip, as these oxides are usually not grown in a controlled manner or might be detrimental to the surface passivation. In this work, an HF dip has been used for removal of the surface oxides both on Si and InP, prior to the deposition of PO$_x$/Al$_2$O$_3$ stacks. On Si, the effect of several other pre-treatments and their effect on the passivation quality of the PO$_x$/Al$_2$O$_3$ stacks have also been investigated. These pre-treatments include a Radio Corporation of America (RCA) clean [97] without removal of the RCA-formed oxide, an HF dip followed by O$_2$ plasma treatment, and an HF dip followed by UV/O$_3$ treatment. Regardless of which pre-treatment was used, high surface passivation quality could be reached with the PO$_x$/Al$_2$O$_3$ stack - which can be seen in the supplementary info Fig. 52 - underlining the robust passivation quality provided by the PO$_x$/Al$_2$O$_3$ stacks.

Fig. 3. Overview of interface properties of passivation schemes on c-Si, namely SiN$_x$ [68-72], PO$_x$/Al$_2$O$_3$ [45-48], SiO$_x$ [71,73-75], SiO$_2$/SiN$_x$ [77,78], a-Si:H [79-81], HO$_2$ [82-84], Al$_2$O$_3$ [86-92], Al$_2$O$_3$/SiN$_x$ [87], and Ga$_2$O$_3$ [93,94]. Interface defect density is shown in (a), while fixed charge density is shown in (b). Note that the fixed charge density can be both positive or negative. Colored bars show ±30% of data points from the median, while the error bars show where ±45% of data points from the median are located.

Fig. 4. Schematic process flow for PO$_x$/Al$_2$O$_3$ surface passivation stacks. Pre-treatment is optional and different pre-treatments can be used. The deposition of the PO$_x$ layer should be followed by in-situ capping with Al$_2$O$_3$. Post-deposition annealing is required to activate passivation. The values indicated in brackets represent the already investigated processing conditions.
[45,46,49] using trimethyl phosphate (TMPO, PO(OCH₃)₃) and an O₂ plasma, and a pulsed-flow plasma-enhanced chemical vapor deposition process (PF-PECVD) [47,48], using TMPO and an O₂ plasma. The main difference between these two processes is whether the precursor (TMPO) and reactant (O₂ plasma) are present in the reactor simultaneously (PF-PECVD) or alternately (PE-ALD). The details of the two POₓ deposition processes are schematically shown in the Supplementary Information Figs. S1a and S1b. Although currently only these two processes have been reported for POₓ passivation layers, other processes for deposition of the POₓ layer are likely also realizable, such as for example continuous CVD.

The in-situ characterization of the PE-ALD and PF-PECVD POₓ layer growth is shown in Fig. 5a and b, respectively. Lower deposition temperatures lead to higher growth per cycles (GPC) for both POₓ deposition processes. The thickness of the POₓ layer is typically kept around 5 nm. The POₓ PE-ALD process shows a significant growth delay on Si, as seen in Fig. 5a. The growth mechanisms of the POₓ layer have not been investigated in detail yet, but it is known that the precursor dose does not reach saturation [45]. This may lead to a buildup of precursor molecules inside the reaction chamber, which could explain why the GPC increases with the number of cycles. Eventually, this buildup of precursor appears to reach a steady state, as after the initial growth delay, the PE-ALD POₓ deposition process does reach linear growth, which can take more than 100 ALD cycles. The steady-state GPCs are about 1.05, 1.02, and 0.52 Å/cycle, for deposition temperatures of 25, 100, and 200 °C, respectively. The small jump in thickness in the first 10 ALD cycles is likely related to the formation of a SiOₓ layer due to the exposure of the silicon surface to the O₂ plasma of the PE-ALD POₓ process.

The POₓ PF-PECVD process has a significantly higher growth rate and requires fewer cycles to obtain the same POₓ film thickness, as can be seen in Fig. 5b. The PF-PECVD process still shows a slight growth delay, similar to the PE-ALD process. However, there is no jump in film thickness observed in the first cycles, as in this particular case the silicon surface was pre-oxidized using an O₂ plasma prior to the start of the POₓ deposition process. At a deposition temperature of 300 °C, there is growth for the PF-PECVD process albeit with a lower GPC, whereas the PE-ALD process at this deposition temperature barely shows any growth.

3.1.3. Al₂O₃ deposition

As exposing the POₓ layer to ambient leads to visible degradation within minutes, it is critical that the POₓ is capped in-situ with a layer that protects the POₓ from the ambient. For the POₓ/Al₂O₃ stacks, Al₂O₃ acts as a capping layer and has been deposited by PE-ALD usingtrimethyl aluminum (TMA, Al(CH₃)₃) and an O₂ plasma. The details of the PE-ALD process are shown schematically in the Supplementary Information Fig. S1c. Besides PE-ALD, other deposition methods such as plasma-enhanced CVD or PF-PECVD [107] for deposition of the Al₂O₃ capping might also be used. In principle any in-situ deposited capping layer could be used to protect the POₓ layer. However, it is important to note, that the Al₂O₃ layer plays a role in the passivation quality provided by the POₓ/Al₂O₃ stack, which will be discussed in more detail in section 4.1.

The in-situ growth of Al₂O₃ on top of the POₓ layer is shown in Fig. 5c. In the first 10 cycles, the GPC of the Al₂O₃ PE-ALD process is slightly reduced as it is growing on the POₓ layer. This slight reduction in growth may be related to mixing of the Al into the POₓ layer, which is known to occur during deposition and will be discussed in section 4.2, and might take place within the first few cycles. However, it could also be related to a slight delay in nucleation which is quite common when growing one layer on top of another. After the first 10 cycles a steady GPC is reached, and linear growth can be observed. The GPC values of the Al₂O₃ PE-ALD process are 1.37, 1.23, 1.15, and 1.04 Å/cycle, for deposition temperatures of 25, 100, 200, and 300 °C, respectively. This decreasing trend in GPC with higher deposition temperature for PE-ALD of Al₂O₃ matches well with reports in the literature for Al₂O₃ grown on silicon, although the reported GPC values at the lower deposition temperatures are slightly higher [108].

3.1.4. Post-deposition annealing

After the deposition of the POₓ/Al₂O₃ stack, a post-deposition annealing treatment is required to activate the passivation, as can also be seen in Fig. 1. The optimal annealing temperature depends on the substrate, where surface passivation of InP requires lower annealing temperatures, in comparison to the surface passivation of Si. On Si, post-deposition annealing leads to passivation of Si dangling bonds by hydrogen originating from the POₓ/Al₂O₃ stack, as well as to the formation of AlPO₄ [47]. The latter will be discussed in more detail in section 4.2. The passivation mechanism of POₓ/Al₂O₃ on InP has not been investigated in detail, but hydrogen is known to not only be able to passivate defects at the Si surface, but also to passivate defects at the surfaces of other semiconductor materials, including InP, GaAs, and Ge [109–112]. Annealing may activate such passivation provided by hydrogen, where the hydrogen originates from the POₓ/Al₂O₃ stack. Annealing at high temperatures leads to depassivation of the surface as also seen in Fig. 1, which may be related to breaking of hydrogen bonds and the effusion of hydrogen.

3.2. Influence of layer thickness

The thicknesses of the POₓ and Al₂O₃ layers in the stack play an important role in the obtained surface passivation quality. It has been shown that the POₓ layer thickness should be around 4–6 nm to reach the optimal passivation quality on c-Si, as a lower thickness leads to a decreased passivation quality [46]. For the Al₂O₃ layer, a thickness of 10 or 15 nm results in the same passivation quality, but Al₂O₃ layer thicknesses <10 nm result in a decrease in passivation quality. On InP,
using a thicker Al2O3 capping layer of 16 nm resulted in higher surface passivation than a 3 nm Al2O3 capping layer (when using a 1 nm thick POx layer), while using 5 nm POx instead of 1 nm resulted in even higher surface passivation [49].

Notably, if the POx layer becomes thicker than ~7 nm, the POx/Al2O3 stack can start to show blistering upon annealing, and for thicker (~10 nm) POx layers, blistering can even occur without annealing. A microscope image of this blistering can be seen in the Supplementary Information Fig. S3. This sort of blistering of a stack of two layers is similar to Al2O3/SiNx stacks, which can also show blistering upon annealing [113,114]. For the Al2O3/SiNx stacks, it has been shown that blistering is the result of the release of hydrogen and other gaseous species such as H2O, from the Al2O3 layer at elevated temperatures, which initiates the blistering of the layers. It has been shown that the POx/Al2O3 stacks have a high hydrogen content (~20 at. %) [47] and from effusion measurements, it is evident that H2 (m/z = 2) and H2O (m/z = 18) effuse from the POx/Al2O3 stacks at temperatures of around 300–400 °C, as shown in Fig. 6. The blistering upon annealing of POx/Al2O3 stacks with a thick (~7 nm) POx layer also occurs at annealing temperatures of around 300–400 °C. Therefore, it is likely that the blistering of the POx/Al2O3 layers follows a similar mechanism as the blistering of the Al2O3/SiNx layers, i.e. the POx layer releases significant amounts of gaseous H2 upon annealing, which can initiate the formation of blisters.

It has been observed that when using a higher pressure (100 mTorr instead of 15 mTorr) when depositing the POx layer, that stacks of 5 nm POx with 10 nm Al2O3 can also start blistering. It is possible that this is related to a higher hydrogen content of the POx layers deposited at higher pressure. For higher deposition temperatures up to 300 °C, no blistering was observed for stacks of 5 nm POx and 10 nm Al2O3. It has not been investigated whether a POx layer thicker than 5 nm results in blistering for these higher deposition temperatures.

3.3. Physical properties

The material properties of POx/Al2O3 stacks are similar to those of Al2O3 films, although the overall mass density and refractive index are lower, which is likely due to the lower mass density and refractive index of the POx layer [47]. Note that mixing and structural changes take place in the stack upon annealing. Therefore, the POx/Al2O3 stacks are treated as single (mixed) layers for determination of the physical properties after annealing. The physical properties of the POx/Al2O3 stacks are summarized in Table 1, where also the physical properties of Al2O3 are added for comparison. While the material properties of Al2O3 films can vary quite significantly with deposition temperature [31], the material properties of POx/Al2O3 do not vary much over the deposition temperature range of 100–300 °C [47]. Note that the phosphorus content in Table 1 is averaged over the entire POx/Al2O3 stack, whereas the phosphorus content in the POx layer is higher, up to around 12 at. %. In the table also the interface properties of POx/Al2O3 and Al2O3 on silicon are listed, namely the interface defect density and the fixed charge density. The values for optical constants $\varepsilon_1$ and $\varepsilon_2$ can be found in the Supplementary Information Fig. S4.

4. Capping layer

4.1. Role of the capping layer on passivation quality

The capping layer of the POx/Al2O3 stacks, i.e. the Al2O3 layer, not only plays the role of protecting the POx layer, but it also plays a role in the passivation quality. This is illustrated in Fig. 7a, where the passivation quality of POx/Al2O3 stacks with an Al2O3 capping layer deposited by thermal ALD and PE-ALD is shown in terms of minority carrier lifetime, where a higher lifetime indicates better passivation quality. Clearly, the choice of co-reactant for the ALD Al2O3 layer affects the passivation quality, even though both capping layers appear to have very similar composition, as shown in Fig. 7b and c. This shows that the capping layer has an influence on the passivation quality provided by the stack and not every capping layer might work as well without optimization. In this case, the passivation provided by the PE-ALD grown Al2O3 layer provided the highest passivation quality, but this is also (so far) the most optimized process for capping of the POx layer.

The difference in passivation quality provided by these two capping layers might also be related to a difference in ability of the Al2O3 layer to act as a hydrogen source and hydrogen effusion barrier [115], as the passivation quality of the POx/Al2O3 stacks is found to be related to surface passivation provided by hydrogen [47]. It is also noted that,

---

**Table 1**

<table>
<thead>
<tr>
<th>Physical property</th>
<th>POx/Al2O3 (100 °C)</th>
<th>POx/Al2O3 (200 °C)</th>
<th>Al2O3 (200 °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase</td>
<td>Amorphous</td>
<td>–</td>
<td>Amorphous</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.57 (at 2.1 eV)</td>
<td>1.56 (at 2.1 eV)</td>
<td>1.64 (at 2.0 eV)</td>
</tr>
<tr>
<td>Optical bandgap</td>
<td>&gt;6 eV (Eg0)</td>
<td>&gt;6 eV (Eg0)</td>
<td>6.4 eV</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>6.4</td>
<td>6.4</td>
<td>7.9</td>
</tr>
<tr>
<td>Mass density</td>
<td>2.7 g/cm²</td>
<td>2.3 g/cm³</td>
<td>3.1 g/cm³</td>
</tr>
<tr>
<td>Hydrogen content</td>
<td>8 at. %</td>
<td>7 at. %</td>
<td>2.4 at. %</td>
</tr>
<tr>
<td>Aluminium content</td>
<td>28 at. %</td>
<td>28 at. %</td>
<td>32-33 at. %</td>
</tr>
<tr>
<td>Phosphorus content</td>
<td>5 at. %</td>
<td>5 at. %</td>
<td>–</td>
</tr>
<tr>
<td>Oxygen content</td>
<td>59 at. %</td>
<td>60 at. %</td>
<td>64-65 at. %</td>
</tr>
<tr>
<td>Interface defect density</td>
<td>5 $\times$ 10¹¹ eV⁻¹ cm⁻²</td>
<td>8 $\times$ 10¹¹ eV⁻¹ cm⁻²</td>
<td>1 $\times$ 10¹¹ eV⁻¹ cm⁻²</td>
</tr>
<tr>
<td>Fixed charge density</td>
<td>4 $\times$ 10¹⁷ cm⁻²</td>
<td>5 $\times$ 10¹⁷ cm⁻²</td>
<td>6 $\times$ 10¹⁹ cm⁻²</td>
</tr>
</tbody>
</table>
because of the hygroscopic nature of the PO\textsubscript{x} layer, deposition using a thermal ALD process with H\textsubscript{2}O as reactant may result in degradation of the PO\textsubscript{x} layer during deposition of the capping layer, which may also lower the passivation quality.

Besides Al\textsubscript{2}O\textsubscript{3}, other capping layers can also be of interest. TiO\textsubscript{2} has been investigated as capping layer on PO\textsubscript{x}, where the PO\textsubscript{x}/TiO\textsubscript{2} stack did not result in any significant surface passivation on silicon, indicating that not all capping layers may result in good passivation. However, this can also be in part related to the blistering observed for this stack. Nevertheless, capping the PO\textsubscript{x} layer with alternative layers (or stacks) may provide opportunities to tailor the (passivation) properties of the resulting stack. It has been reported that deposition of a SiN\textsubscript{x} layer on top of the PO\textsubscript{x}/Al\textsubscript{2}O\textsubscript{3} layers can protect the PO\textsubscript{x}/Al\textsubscript{2}O\textsubscript{3} from degradation during a high temperature firing process. The resulting PO\textsubscript{x}/Al\textsubscript{2}O\textsubscript{3}/SiN\textsubscript{x} stack showed improved passivation quality as compared to the fired PO\textsubscript{x}/Al\textsubscript{2}O\textsubscript{3} stacks without SiN\textsubscript{x} [48]. Possibly, a PO\textsubscript{x}/SiN\textsubscript{x} stack without intermediate Al\textsubscript{2}O\textsubscript{3} layer might also lead to good passivation, as SiN\textsubscript{x} is also frequently used as a capping layer.

4.2. Mixing of the PO\textsubscript{x} and capping layer

It has been reported that aluminum from the Al\textsubscript{2}O\textsubscript{3} layer mixes into the PO\textsubscript{x} layer [47]. The mixing of the Al\textsubscript{2}O\textsubscript{3} and PO\textsubscript{x} layers can also be seen in Fig. 7a and b, where the Al signal clearly persists in the PO\textsubscript{x} region. This mixing of Al into the PO\textsubscript{x} layer can also be seen for PO\textsubscript{x}-/Al\textsubscript{2}O\textsubscript{3} on InP [49]. The mixing of the capping layer with the PO\textsubscript{x} layer happens already during deposition, and the mixing of the layers itself is not limited to just Al\textsubscript{2}O\textsubscript{3} and PO\textsubscript{x}. When using TiO\textsubscript{2} as a capping layer, infiltration of Ti in the PO\textsubscript{x} layer in the as-deposited state can also be observed, which can be seen in the Supplementary Information Fig. S5. As this mixing happens for these various capping layers, it is likely related to the hygroscopic nature of the PO\textsubscript{x} layer and such mixing can be expected to also occur when using other capping layers. The mechanism for the mixing is not yet established, although some explanations have been proposed, including mixing due to a highly porous PO\textsubscript{x}, a low melting point and glass transition temperature of the PO\textsubscript{x} layer (lower than the deposition temperature), and interface reactions occurring between the PO\textsubscript{x} layer and the capping layer [47].

Although mixing of the Al\textsubscript{2}O\textsubscript{3} and the PO\textsubscript{x} layer occurs already during deposition, upon annealing structural changes occur, which lead to the formation of AlPO\textsubscript{4} [47]. This can be seen in Fig. 8a, where the infrared spectra of the PO\textsubscript{x}/Al\textsubscript{2}O\textsubscript{3} stacks are plotted for as-deposited and annealed conditions. The structural changes lead to the formation of a prominent peak at 1100 cm\textsuperscript{-1}, which indicates the formation of AlPO\textsubscript{4}, and a reduction in signals at 1250 and 950 cm\textsuperscript{-1}. These structural changes start to be visible already when annealing at 250 °C, and are more apparent when annealing at 400 °C. In Fig. 8b, Time-of-Flight Secondary Ion Mass Spectrometry (ToF-SIMS) depth profiles for the same as-deposited and annealed PO\textsubscript{x}/Al\textsubscript{2}O\textsubscript{3} stacks from Fig. 8a are shown. The ToF-SIMS depth profiles show the presence of Al in the PO\textsubscript{x} layer in the as-deposited state, showing the mixing of the layers, and upon annealing, the signals of Al\textsuperscript{3+} and P\textsuperscript{5+} change to some degree, consistent with the structural changes seen in infrared spectroscopy in the same annealing temperature range. The changes due to annealing consist of a broadening of the P\textsuperscript{5+} signal into the Al\textsubscript{2}O\textsubscript{3} layer and a flattening of the Al\textsuperscript{3+} signal in the PO\textsubscript{x} layer. Besides changes in the Al\textsuperscript{3+} and P\textsuperscript{5+} signal upon annealing, also the H\textsuperscript{+} signal decreases upon annealing at T > 250 °C. Specifically, the peak in H\textsuperscript{+} at the Al\textsubscript{2}O\textsubscript{3}/PO\textsubscript{x} interface disappears upon annealing at 400 °C and the peak in H\textsuperscript{+} at the PO\textsubscript{x}/Si interface is reduced. The coincidence between hydrogen effusion (see Fig. 6) starting near 200 °C with a maximum near 400 °C, the out-diffusion of hydrogen according to SIMS (between 250 and 400 °C, see Fig. 8b) and the formation of AlPO\textsubscript{4} according to infrared spectroscopy (mostly between 250 and 400 °C, see Fig. 8a) suggest a correlation between the formation of AlPO\textsubscript{4} and the effusion of hydrogen predominantly from the PO\textsubscript{x} (AlPO\textsubscript{4}) layer including the interfaces. We note that at the PO\textsubscript{x}/Si interface hydrogen can react with silicon dangling bonds and passivate them [116]. These results suggest that the low interface defect density achieved with the Al\textsubscript{2}O\textsubscript{3}/PO\textsubscript{x} stacks is likely not just related to hydrogen diffusion from a passivation layer as frequently observed for single layer passivation schemes [23], but also due hydrogen mobilized by a chemical reaction. Furthermore, the formation of AlPO\textsubscript{4}, which is structurally analogous to SiO\textsubscript{2} [117], may also lead to some surface passivation.

For deposition temperatures of 200 °C and 300 °C, the comparison between infrared spectra and ToF-SIMS can be found in the Supplementary Information Fig. S6, where it is shown that at higher deposition temperatures, less structural and compositional changes in the PO\textsubscript{x} layer are observed for single layer passivation schemes [23], but also due hydrogen mobilized by a chemical reaction. Furthermore, the formation of AlPO\textsubscript{4}, which is structurally analogous to SiO\textsubscript{2} [117], may also lead to some surface passivation.
5. Towards device integration

5.1. Conformality

As device dimensions continue to scale down and high-aspect-ratio and complex 3D shaped device structures become more common, the conformality of thin film deposition processes becomes more critical. Flux controlled deposition techniques, such as CVD and physical vapor deposition (PVD), can have limited conformality, because for example, the flux of reactant molecules can be orders of magnitude higher at the entrance of a trench than inside the trench, leading to higher growth rates at the entrance [118]. For ALD, the surface-controlled nature of the deposition process allows for reactant molecules to diffuse deep into a trench and a higher probability to coat the entire structure conformally through the self-limiting surface reactions. For integration of PO$_x$/Al$_2$O$_3$ in devices, the choice between ALD or CVD most likely depends on aspect ratio, complex 3D structures, processing throughput, and the desired thickness control.

In Fig. 8, changes in PO$_x$/Al$_2$O$_3$ stacks due to annealing determined by (a) infrared spectroscopy spectra for PO$_x$/Al$_2$O$_3$ deposited at 100 °C from Theeuwes et al. [47] and (b) Time-of-Flight Secondary Ion Mass Spectrometry (ToF-SIMS) depth profiles of the same PO$_x$/Al$_2$O$_3$ stacks. The layer thicknesses were 5 nm for the PO$_x$ layer and 10 nm for the Al$_2$O$_3$ layer. Note the depth profiles were shifted to overlap the $^{29}$Si$^-$ signal and the intensities of H$^-$ signals were multiplied by 10x to improve readability of the figure.

In Fig. 9, TEM images of three different types of structures coated with PO$_x$/Al$_2$O$_3$ stacks are shown, namely flat silicon, textured silicon, and an InP nanowire. Both an overview image of the structure itself, as well as a close-up of the interface between the PO$_x$/Al$_2$O$_3$ and the semiconductor are shown. In all cases, the structures are coated conformally by the PO$_x$/Al$_2$O$_3$ stacks. For the flat and textured silicon, the PO$_x$/Al$_2$O$_3$ stacks were deposited by PF-PECVD. On the InP nanowire, the PO$_x$/Al$_2$O$_3$ stack was deposited by PE-ALD. Energy-dispersive X-ray
spectroscopy (EDX) maps of the PO$_x$/Al$_2$O$_3$ stacks on textured silicon and InP nanowire are shown in the Supplementary Information Figs. S7 and S8, respectively.

5.2. Stability

For device applications, it is important that layers remain stable over an extended period of time, such that the device performance does not degrade significantly over time. Fig. 10 shows how the passivation quality of the PE-ALD and PF-PECVD PO$_x$/Al$_2$O$_3$ layers on silicon changes over time for samples kept in ambient conditions. The passivation quality here is presented in terms of the recombination parameter $J_0$ [119], which represents a measure for the amount of charge carrier recombination, where a lower value indicates better passivation quality. The solid lines represent a least-square fit through the data, which show that on average there is only a very slight increase in $J_0$ over time, indicating a very slight decrease in passivation quality. The degradation is similar for both the PE-ALD and PF-PECVD processes, as indicated by the similar slope of the straight-line fits. Such gradual degradation may simply be due to sample handling damage (like scratches) commonly observed to accumulate over multiple such measurements.

6. Conclusion

In this review, the latest insights of the PO$_x$/Al$_2$O$_3$ stacks for semiconductor surface passivation were summarized and elaborated upon. PO$_x$/Al$_2$O$_3$ stacks provide excellent surface passivation of Si and InP, which is enabled by the unique properties of the PO$_x$/Al$_2$O$_3$ stacks, including a high positive fixed charge density, a low interface defect density, and a wide deposition temperature range.

PO$_x$/Al$_2$O$_3$ stacks can be deposited using various deposition processes, which include PE-ALD and PF-PECVD processes, and several different pre-treatments may be used in prior to deposition of the PO$_x$/Al$_2$O$_3$ stack, without significantly impacting the surface passivation. Post-deposition annealing plays an important role for the surface passivation, as it activates the chemical passivation, which is related to passivation provided by hydrogen and the formation of AlPO$_4$.

The Al$_2$O$_3$ capping layer is required to protect the hygroscopic PO$_x$ layer from reacting with ambient. However, the Al$_2$O$_3$ layer also plays a role in the passivation provided by the PO$_x$/Al$_2$O$_3$, likely due to its role as hydrogen source and hydrogen effusion barrier. Furthermore, the Al$_2$O$_3$ capping layer mixes into the PO$_x$ layer during deposition, which upon annealing leads to the formation of AlPO$_4$. Instead of capping by Al$_2$O$_3$, the PO$_x$ layer by other thin films may provide opportunities to tailor the properties of the resulting stack.

The surface passivation provided by the PO$_x$/Al$_2$O$_3$ stacks on silicon is stable for over 1000 days and high-aspect-ratio structures, such as nanopores, can be conformally coated. Therefore, PO$_x$/Al$_2$O$_3$ stacks may be used in devices featuring complex 3D structures.

The understanding gained on the PO$_x$/Al$_2$O$_3$ stacks can enable the adoption of PO$_x$/Al$_2$O$_3$ stacks as a passivation scheme in Si and InP devices, including solar cells, FETs, LEDs, and lasers. Moreover, the unique properties of the PO$_x$/Al$_2$O$_3$ may enable opportunities for surface passivation of alternative semiconductor materials, including germanium and III-V semiconductors.

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CRediT authorship contribution statement

Roel J. Theeuwes: Writing – original draft, Visualization, Investigation, Conceptualization. Jimmy Melskens: Writing – review & editing, Supervision, Investigation, Funding acquisition. Wolfhard Beyer: Writing – review & editing, Investigation. Uwe Breuer: Writing – review & editing, Investigation. Lachlan E. Black: Writing – review & editing, Investigation. Wilhelmus J.H. Berghuis: Writing – review & editing, Investigation. Bart Macco: Writing – review & editing, Supervision, Investigation, Funding acquisition. Wilhelmus M.M. Kessels: Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: W.M.M. Kessels has patent pending to Eindhoven Technical University.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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