ARTICLE IN PRESS

Nuclear Instruments and Methods in Physics Research A ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Atomic Layer Deposition (ALD) grown thin films for ultra-fine pitch pixel detectors

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ARTICLE INFO

Article history:
Received 6 November 2015
Received in revised form
10 March 2016
Accepted 11 March 2016

Keywords:
ALD
TiN
Detector
Bias resistor

ABSTRACT

In this report we cover two special applications of Atomic Layer Deposition (ALD) thin films to solve these challenges of the very small size pixel detectors. First, we propose to passivate the p-type pixel detector with ALD grown Al_2O_3 field insulator with a negative oxide charge instead of using the commonly adopted p-stop or p-spray technologies with SiO_2, and second, to use plasma-enhanced ALD grown titanium nitride (TiN) bias resistors instead of the punch through biasing structures. Surface passivation properties of Al_2O_3 field insulator was studied by Photoconductive Decay (PCD) method and our results indicate that after appropriate annealing Al_2O_3 provides equally low effective surface recombination velocity as thermally oxidized Si/SiO_2 interface. Furthermore, with properly designed annealing steps, the TiN thin film resistors can be tuned to have up to several MΩ resistances with a few μm of physical size required in ultra-fine pitch pixel detectors.

1. Introduction

The Large Hadron Collider (LHC) at CERN will need a major upgrade after 2020 to maintain the scientific progress and exploit its full capacity. In this so-called High-Luminosity LHC (HL-LHC) the pixel detectors used in the particle tracking systems will be subjected to irradiation fluences up to 1×10^{16} n_{eq}/cm^2. Under such conditions, the effective charge collection distance will be in the order of 20–40 μm, before the charge carriers get trapped into radiation induced defects [1]. In the currently used pixel detectors the pixel size, however, is in the order of 100 μm × 100 μm [2]. An obvious approach to maintain a sufficiently good overall efficiency is to increase the detector granularity by downscaling the pixel size to be comparable to the charge collection distance. Furthermore, by using n^+ segmentation on p-type silicon (p-type detectors) one can benefit from the the three times higher drift velocity of the electrons compared to the holes. In addition, unlike the n-type silicon, p-type does not undergo space charge sign inversion (SCSI) and the electric field maximum thus remains on the segmented side even after heavy irradiation [3,4]. A commonly known difficulty of the $n^+/p^-/p^+$ devices, however, is the more complex fabrication technology caused by the need to compensate the electron accumulation near the Si–SiO_2 interface due to the positive oxide charge in SiO_2 by the p-spray or p-stop techniques [5]. We propose a different approach to overcome the near-surface electron accumulation at the Si–SiO_2 interface by depositing a thin film field insulator with a negative oxide charge on top of the silicon wafer after the ion implantations and prior to the remaining processing steps. This thin film must have negative oxide charge, electrically high-quality oxide-silicon interface and sufficient dielectric strength against electrical breakdown [6]. Aluminum oxide (Al_2O_3) grown by Atomic Layer Deposition (ALD) method fulfills all these requirements. ALD is a special case of more commonly adopted Chemical Vapor Phase Deposition thin film growth method. ALD is based on successive, separated and self-terminating gas–solid reactions of typically two originally gaseous or liquid reactants called precursors. The separation of the two reactants is accomplished by the pulsed introduction of an inert purge gas (for example nitrogen or argon) after each pulsed deposition of a reactant in order to remove excess gaseous precursor and reaction by-products from the process chamber prior to the following deposition cycle [6–8]. In addition to oxides, the ALD technology it is also suitable for depositing metal-nitride thin films with high precision, uniformity and resistance

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http://dx.doi.org/10.1016/j.nima.2016.03.037
0168-9002/© 2016 Published by Elsevier B.V.

Please cite this article as: J. Härkönen, et al., Nuclear Instruments & Methods in Physics Research A (2016), http://dx.doi.org/10.1016/j.nima.2016.03.037

density [9]. Pixel detectors are often resistively biased using punch-through structures because of the current-voltage (IV) probing needed for their quality assurance prior to the Flip-Chip (FC) bonding and module assembly processes. Bias resistors can also be used for this purpose, but the most commonly adopted bias resistor technology is based on doped poly-silicon and thus, the resulting resistor structure is typically too large for the use in pixel detectors [2]. In fact, both of these technologies are even more difficult to downscale into small dimensions while simultaneously maintaining MΩ range resistance. Thus, in this report two potentially interesting applications of the ALD thin film technology for solving the challenges of the very small size pixel detectors are presented. First introduces the passivation of the p-type silicon particle detector with ALD grown Al_2O_3 field insulator with negative oxide charge, and second the plasma-enhanced ALD grown titanium nitride (TiN) as a potential candidate for a thin film metal bias resistor.

2. Passivation by ALD grown Al_2O_3

We have studied the electrical passivation properties of the ALD grown Al_2O_3 by Photoconductive Decay (μPCD) method. In the μPCD method the lifetime is measured by illuminating the wafer by a laser pulse and then monitoring the transient of the decaying carrier concentration by using a microwave signal. The lifetime is extracted from the conductivity transient [10,11]. The μPCD measurement is contactless, non -destructive and if automated, a large number of measurement points can be mapped in a short time. PCD measures the effective minority carrier recombination lifetime (τ_{eff}), which is (as shown in Eq. (1)) a combination of the bulk lifetime (τ_{b}) and the surface recombination limited lifetime (τ_{sr}),

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_b} + \frac{1}{\tau_{sr}} \quad (1)$$

The equation implies that if the surface recombination velocity approaches zero, the measured lifetime approaches the bulk lifetime and hence, the relationship can be used as a quantitative measure of the electronic properties of the semiconductor insulator interface [12]. If the carrier lifetime in the bulk is very high, which is often the case in the detector grade high-purity and high-resistivity materials, the measured effective lifetime is limited by the surface recombination velocity.

The surface passivation properties [13,14] of the ALD grown Al_2O_3 was studied by first measuring the lifetime in a thermally dry oxidized high-resistivity n-type magnetic Czochralski silicon (MCz-Si) wafer produced by Okmetic Ltd. A histogram of the effective lifetime values is shown in Fig. 1.

The oxidized wafer was mapped with 230 data points, with a median of 4812 μs, a standard deviation of 1565 μs and a most probable value (MPV) of 4700 μs. After the lifetime measurement the SiO_2 was removed from the other side of the wafer by buffered HF dip. The Al_2O_3 was deposited on the clean silicon surface by a Beneq TFS-500 ALD reactor. Between the HF treatment and ALD deposition, the clean Si surface was subjected to the ambient air approximately 5–15 min. The Al_2O_3 deposition process was using two precursors, trimethylaluminium $Al(CH_3)$ and water (H_2O), which were sequentially pulsed into the growth chamber of the ALD reactor by nitrogen carrier gas. The deposition temperature was 220 °C and the number of the ALD cycles was 500, resulting in the oxide film thickness of 52 nm. The lifetime measurement was repeated for the wafer with the as-grown Al_2O_3. After the measurement the wafer was sintered in nitrogen ambient at 370 °C for 30 min, which is the same recipe as we frequently use for sintering

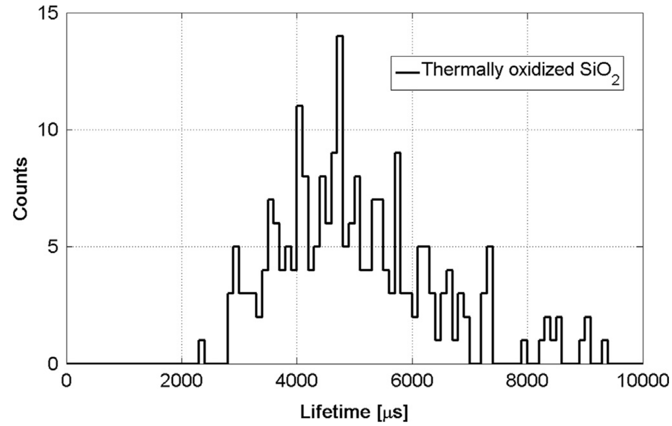

Fig. 1. A histogram of the lifetime data measured from a high-resistivity MCz-Si wafer oxidized at 1100 °C for 30 min resulting in 25 nm thick SiO_2. During the PCD measurement both surfaces were Corona charged to +600 μC charge in order to provide a field effect preventing the diffusing laser induced electrons to recombine into the surface states.

the aluminum electrodes in our detector process. Fig. 2. shows the histograms of the lifetime measurements for the as-grown and sintered Al_2O_3 thin films.

It can be seen in Fig. 2a that the lifetime is peaking sharply around the most probable value of 600 μs. The median value is 610 μsand the standard deviation is only 45 μs. The almost an order of magnitude lower effective lifetime together with the narrow distribution indicate that the measurement was dominated by the surface recombination at the silicon–Al_2O_3 interface. The histogram of the lifetime after sintering in Fig. 2b is essentially different. The MPV peaks at 5100 μs, the median is 5370 μswith the standard deviation of 1075 μs indicating clearly higher effective lifetime values with respect to the case where the same wafer was entirely passivated by the SiO_2.

The passivation properties of the ALD grown Al_2O_3 were further studied by the current-voltage (IV) measurements of diced 300 μm thick $n^+/p^-/p^+$pad detectors made of p-type Float Zone silicon (FZ-Si) and having a 5 mm × 5 mm active area surrounded by a multi-guard ring structure. The diodes had no p-stop structures or p-spray implants [18]. The current was measured at the room temperature with two Keithley 2410 SMUs, one of them connected with a probe needle into the active area center contact and the other one connected to the 100 μm wide primary guard ring surrounding the center pad contact. The results can be seen in Fig. 3.

The full depletion voltages (V_{fd}) of the p-type Fz-Si diodes used for the IV-measurement were in the scale of 60–70 V. It can be seen from the Fig. 3a and b that there is no breakdown below −500 V bias. In one of the cases, guard ring current shows a tendency for a "soft" breakdown after −400 V. The center current of the diodes saturates to few nA after the full depletion voltage (V_{fd}).

3. ALD grown TiN thin film bias resistors

As previously mentioned, with the ALD technology it is also possible to deposit metal-nitride thin films with high precision, uniformity and repeatability. For the fine pitch pixel devices very high resistivity of the material is desirable. Furthermore, the material should be compatible with the silicon processing and in