Thin Photodiodes for a Neutron Scintillator Silicon-Well Detector

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Abstract—In the development of new neutron imaging applications, it is crucial to achieve a detector combining high spatial resolution, fast response, and high detection efficiency. To achieve such features, we have proposed a new design for position sensitive radiation sensors, which we called the micromachined Si-well scintillator pixel detector. It consists of an array of scintillator crystals encapsulated in silicon wells with photodiodes at the bottom. In the following, we describe such a detector, which makes use of a powder of ${}^6\text{Li}^{158}\text{Gd}(\text{BO}_3)_3(\text{Ce}^{3+})$. The first experiments obtained with a prototype detector using a thermal neutron beam show the presence of a signal above the detector noise tail. In addition, to improve the characteristics of the well-type silicon sensor, we have investigated the deep reactive ion etching on silicon-on-insulator wafers. The process to etch 700- μm -wide vertical wells into a 500- μm -thick silicon wafer has been optimized. Test detectors with 10- μm -thick photodiodes at the bottom have been fabricated by means of this process.

Index Terms—Micromachining, neutron detectors, photodiodes, position-sensitive particle detectors, silicon-on-insulator technology.

I. INTRODUCTION

THE DETECTION of thermal neutrons can be performed by means of a scintillation crystal coupled to a silicon photodiode. When position sensitivity is needed, one can couple a large crystal to an array of silicon photodiodes. However, the resulting sharing of the scintillation light by several pixels together with the electronic noise of the diodes degrades the detection efficiency and the spatial resolution of such a device. To confine the lateral spread without too much loss of light, we have proposed to encapsulate the scintillation material in a well-type silicon sensor [1] (Fig. 1). The latter can be realized by means of wells etched in a silicon wafer using deep reactive ion etching. The bottom of the well can be rather thin, with just enough silicon left for efficient light absorption in a diode. Scintillator crystal material can be deposited in the wells, e.g.,

Fig. 1. Schematic of the proposed micromachined Si-well scintillator pixel detector (cross section, not to scale).

Fig. 2. Schematic of the thin test photodiode (not to scale).

by evaporation techniques or as a powder with a binder. The thermal neutron absorption efficiency of a 500- μm -thick layer of ${}^6\text{Li}^{158}\text{Gd}(\text{BO}_3)_3$ powder is higher than 60% (powder packing fraction of 50%), according to Monte Carlo simulations using the CERN-based GCALOR interface for GEANT.

Our first effort was to fabricate and characterize the thin photodiodes needed for this application. The 3×3 arrays include 1.3-mm-wide N⁺⁺NP avalanche photodiodes processed in the 10- μm -thick membranes that remain after the thinning of ~530- μm -thick (100) silicon wafers by means of potassium hydroxide (KOH) solution (Fig. 2). We have reported the diode characteristics and the first results of scintillation light readout obtained with these diodes in combination with several scintillator materials for γ -ray detection in [1] and [2]. Recently, we have filled the wells with a powder of $\text{Li}_6\text{Gd}(\text{BO}_3)_3(\text{Ce}^{3+})$ enriched in ${}^6\text{Li}$ and using separated ${}^{158}\text{Gd}$ for neutron detection [3]. In the following, we report the first results obtained with a thermal neutron beam of the nuclear reactor of the Delft University.

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Furthermore, thin photodiodes have been fabricated in vertical wells by means of another etching method: the cryogenic deep reactive ion etching. Except for the thickness of the sidewalls, these sensors present the adequate geometry shown in Fig. 1. The $\sim 10\text{-}\mu\text{m}$ -thick diodes, which are positioned at the bottom of $500\text{-}\mu\text{m}$ -deep and $700\text{-}\mu\text{m}$ -wide vertical wells, have been characterized in terms of noise and light detection efficiency. Results are presented.

II. THERMAL NEUTRON DETECTION MEASUREMENTS

The thin avalanches test photodiodes described in [1] and [2] (Fig. 2) have been coupled with a powder of $\text{Li}_6\text{Gd}(\text{BO}_3)_3$ activated with Ce^{3+} enriched in ^6Li and using separated ^{158}Gd (Fig. 3). A binder has been added that is simultaneously a wavelength shifter, emitting at 600 nm . This is needed as the $\text{Li}_6\text{Gd}(\text{BO}_3)_3(\text{Ce}^{3+})$ scintillator emits in the blue region (400 nm) where the quantum efficiency of the photodiodes is very low. The scintillator powder was covered with a reflective layer consisting of a MgO white powder plus four layers of Teflon tape. First neutron detection measurements have been performed making use of a thermal neutron beam of the nuclear reactor of the Delft University of Technology. The pulse height spectrum shown in Fig. 4 has been obtained at $3\text{-}\mu\text{s}$ shaping time and 65-V bias voltage. It shows the presence of a signal above the detector noise tail. The bump between channels 30 and 80 corresponds to a signal of $2000\text{--}5000$ electrons in the diode. The response of the diode-amplifier system is calibrated with X-rays from an ^{55}Fe source, absorbed in the silicon diode.

At a bias voltage of 65 V , the gain of the diode at 675-nm wavelength is about two. Assuming a light yield of $\sim 50\,000$ photons/neutron [3], this results in a low light-detection efficiency of $2\%\text{--}5\%$. This is comparable with the scintillation light measurements that we performed with these detectors in combination with a $\text{CsI}(\text{Tl})$ scintillation crystal. The emission spectral distribution of this scintillator is maximal at 565 nm , and we obtained a light detection efficiency of $\sim 6\%$ [2]. The diodes suffer from a $\sim 3\text{-}\mu\text{m}$ -thick dead layer with a rather low transmission of about 40% at 675 nm . In addition, the diodes are covered with a 4-nm -thick native oxide with a transmission of 65% . This results in a total light detection efficiency of $\sim 26\%$ at 675 nm . However, the low light-detection efficiency that we have measured is mainly due to the poor collection of the scintillation light. It is partially due to the oblique sidewalls, which make an angle of 54.73° to the surface (Fig. 2). Furthermore, one must take into account the efficiency of the wavelength shifter and the light transport in the powder material. The fact that a total absorption peak is absent is due the leakage of a large percentage of the produced 2.75-MeV tritons leading to incomplete energy deposition. The range of the triton in $\text{Li}_6\text{Gd}(\text{BO}_3)_3$ is about $50\text{ }\mu\text{m}$, while the scintillation powder consists of crystal grains of which the diameter ranges from ~ 10 to $300\text{ }\mu\text{m}$.

The gamma-ray background has been evaluated by placing in front of the detector a 10-mm -thick $^{10}\text{B}_4\text{C}$ plastic plate to stop the thermal neutrons (Fig. 4). The signals due to the gamma-rays of 478 keV from the absorption of neutrons in boron are submerged in the noise. From these measurements, one can deduce that the neutron signal between channels 30 and 80 is more

Fig. 3. Top photo of the 3×3 array of thin avalanche photodiodes covered with a powder of $^6\text{Li}_6^{158}\text{Gd}(\text{BO}_3)_3(\text{Ce}^{3+})$. The dotted lines are 2 mm apart.

than two orders of magnitude higher than the gamma-ray background. The low-intensity response above channel 80 is presumably from neutrons absorbed close to the diode surface, resulting in higher signals. This signal is mixed with the background resulting from, e.g., the characteristic K X-rays of Gd (43 keV) directly absorbed in the diode. Above channel 80, the gamma-background is one order of magnitude lower in intensity (Fig. 4). The signal at the upper limit of the spectrum ($3 \times 10^5\text{--}10^6$ electrons; Fig. 5) is the background resulting from the triton or alpha leakage depositing up to $\sim 2\text{ MeV}$ in the thin silicon photodiode.

III. THIN PHOTODIODES FABRICATED BY MEANS OF DEEP REACTIVE ION ETCHING

A. Processing

To obtain vertical wells in a silicon wafer, instead of KOH wet chemical etching, we have investigated the cryogenic deep reactive ion etching (DRIE). This is a dry etching technique, which is based on the use of a plasma. The latter provides the gas phase etching environment, which consists of radicals and positive or negative ions. The removal of silicon atoms from the wafer is obtained by chemical reactions with radicals. The gas that we have used is sulfur hexafluoride/oxygen (SF_6/O_2). To etch vertically, the ion beam assisted radical etcher technique was used, where the radical etching is accompanied by a directed ion flux.

The optimization of the deep reactive ion etching to fabricate $700\text{-}\mu\text{m}$ -wide and $500\text{-}\mu\text{m}$ -deep vertical wells into a silicon wafer has been performed with the commercial etcher Plasmalab System 100 from Oxford Instruments, with an inductive coupled plasma source. The new well-type silicon sensors have been fabricated from silicon-on-insulator (SOI) wafers (Fig. 6). The diodes are first processed in the thin Si layer, which is 10

Fig. 4. Pulse height spectrum measured at 65-V bias voltage and 3- μ s shaping time. The noise tail (gray) has been subtracted from both the neutron and gamma-background spectra.

Fig. 5. Pulse-height spectrum up to 1.5 MeV of energy directly absorbed in the diode, measured at 65-V bias voltage and 3- μ s shaping time.

μ m thick with a resistivity of 10–20 Ω ·cm. The design of the diode is similar to the one depicted in Fig. 2. The diodes are 700 μ m wide, separated by 200- μ m-wide vertical silicon sidewalls. The last step of the process is the etching of the vertical wells in the handle top wafer, which is 500 μ m thick (Figs. 6 and 7). The 0.5- μ m-thick oxide layer at the interface of the two Si layers is used as a stopping layer during the etching.

B. Noise and Light Detection Measurements

The breakdown voltage of the 10- μ m-thick photodiodes has been measured to be about 80 V. A higher breakdown voltage was expected. According to MEDICI simulation, a diode with a resistivity of 10 Ω ·cm should be fully depleted at 150-V bias

Fig. 6. Schematic of the vertical well-type silicon sensor (cross-section, not to scale).

voltage, assuming that the thickness of the diode is about 12 μ m, that is, the $\sim$ 2- μ m-thick epilayer (Fig. 2) in addition to

Fig. 7. Top photos of vertical well-type silicon sensors fabricated by means of deep reactive ion etching of 500- μm -thick SOI wafers. The diodes, at the bottom of the wells, are $\sim 10\text{ }\mu\text{m}$ thick and 700 μm wide. The vertical silicon sidewalls are 200 μm wide.

the 10- μm -thick bonded wafer. Then the electric field would be about $2.7 \times 10^5\text{ V/cm}$ at the junction resulting in an amplification process. At 80-V bias voltage, the diodes operate with an electric field that is below $2 \times 10^5\text{ V/cm}$. This is not sufficient to obtain an amplification process.

Close to the breakdown voltage, at 80-V bias voltage, the leakage current is typically between 100 and 300 pA. The diodes show a high junction capacitance due to the thin depletion region, about 10 pF at 80-V bias voltage. When the detector is slightly cooled down to 10 $^\circ\text{C}$ with a Peltier element, the leakage current becomes a minor contribution to the noise. The optimum shaping time is then 10 μs , and we have measured at a bias voltage of 65 V a full-width half-maximum (FWHM) of 1.3 keV at the 13.9-keV peak of ^{241}Am . This is comparable to what has been obtained with the thin avalanche photodiodes fabricated by means of KOH etching (1.5-keV FWHM measured at the 5.89-keV $\text{K}\alpha$ peak of ^{55}Fe at room temperature [1]).

Measurements on light detection have been performed with a 675-nm pulsed laser. Normalization has been performed using two 0.81- cm^2 PIN photodiodes from which the light detection efficiency is about 70% at 675 nm. At room temperature, a compromise between the electronic noise and the light detection is found at a bias voltage of 65 V and a shaping time of 6 μs . On the one hand, a higher bias voltage reduces the silicon dead layer, and consequently enhances the optical response. On the other hand, the leakage current increases, and accordingly the electronic noise increases. At 65 V and

room temperature, the equivalent noise charge (ENC) is 155 electrons (rms), using a low-noise charge-sensitive preamplifier and an ORTEC/EG&G 672 spectroscopy amplifier coupled to an ORTEC/EG&G AD114 analog-to-digital converter. The light detection efficiency is $\sim 43.5\%$ (62% relative to the PIN photodiode). At 10 $^\circ\text{C}$, the optimum is found at a longer shaping time of 10 μs and a bias voltage of 70 V. The ENC is about 128 rms electrons and the light detection efficiency is $\sim 45.5\%$. The light detection efficiency is thus still degraded by a thin silicon dead layer. However, it is enhanced in comparison with that of the former type of thin photodiodes ($\sim 26\%$ light detection efficiency at 675 nm).

IV. CONCLUSION

The thin avalanche photodiode fabricated by means of KOH etching presents a low light-detection efficiency due to a $\sim 3\text{-}\mu\text{m}$ -thick silicon dead layer. In combination with the $\text{Li}_6\text{Gd}(\text{BO}_3)_3(\text{Ce}^{3+})$ scintillation powder for neutron detection, the light detection efficiency has been measured to be as low as 2%–5%. Nevertheless, results of the first experiments using a thermal neutron beam show the presence of a signal above the detector noise tail, demonstrating the feasibility of such a device. To improve the characteristics of the well-type silicon sensor, we have investigated deep reactive ion etching of SOI wafers. The new detectors present a much better geometry for the collection of the scintillation light: the wells are vertical while those fabricated by means of KOH etching are truncated pyramidal holes. In addition, with the new process, the electronic noise of the 10- μm -thick photodiodes has been slightly reduced and the light detection efficiency at 675 nm, the wavelength of the test laser, has been enhanced from 26% to about 45%. The combination of the new vertical well-type sensors and the $\text{Li}_6\text{Gd}(\text{BO}_3)_3(\text{Ce}^{3+})$ powder has to be tested.

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