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The effect of different dicing methods on the leakage currents of n-type silicon diodes and strip sensors

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ABSTRACT

All silicon wafers are singulated into individual chips after device processing (front-end) and before packaging. Silicon wafer singulation is dominated by blade- and laser-dicing techniques, both leave some damage. We are using scribing and cleaving to singulate silicon radiation detectors. Scribing and cleaving is known to leave almost damage free sidewalls when applied to III–V compound semiconductors. The technique is not well developed for dicing silicon devices. We used silicon sensors working in a full depletion mode to determine the damage from different scribing techniques (laser-, diamond, and etch-scribing). Etch-scribing shows very low leakage currents and enables cuts at the edge of the active area of the sensor/die. Furthermore, the leakage currents for laser- and diamond-scribed devices can be reduced by a gaseous sidewall etch step.

1. Introduction

The standard way to dice a semiconductor wafer is blade cutting (dicing is sometimes also called die singulation). Traditional blade dicing leaves mechanical damage, e.g. micro-cracks and chipping at the edges. Furthermore, the blade rotation induces strong mechanical vibrations. Sensitive devices, like some MEMS (Microelectromechanical systems) devices, can be damaged by these vibrations. The blade is also water-cooled during operation. Water-sensitive devices can not be cut by blade dicing. An alternative to blade dicing is cleaving along a scribe line. The scribe can be made by laser or diamond-scribing. Both techniques leave some damage, although much less than classical blade dicing. The combination of scribing and cleaving/breaking is called a dry process dicing because no water cooling is needed [1]. Lei et al. wrote a recent review on modern die singulation techniques [2].

Cleaving is commonly done for III–V compound semiconductor devices [3,4]. GaAs or InP optoelectronic devices are routinely scribed and cleaved. The classical example is the fabrication of laser diodes; a mirror-like sidewall is traditionally formed by cleaving the semiconductor wafer. The cleaved surface has very low damage and is nearly atomically flat, making it ideal for laser applications. III–Vs are brittle and tend to cleave easily following the {1 1 1} crystal planes. Furthermore, the wurtzite crystal structure helps during cleaving, generating an anisotropy for different planes. Silicon is also a brittle material that cleaves preferentially along the {1 0 0} crystal planes. However, one can also cleave along the {1 1 0} planes, if the cleaving force is applied accordingly. Since it is more difficult to cleave silicon than an III–V semiconductor, silicon is normally scribed along a line prior to cleaving. In this study we investigate different ways of silicon scribing. Laser-scribing is the most common way of silicon scribing [5,6]. It is also possible to scribe silicon with a diamond [7]. Both techniques leave some damage at the edge. Laser scribing can lead to a heat-affected zone in the silicon. The quantity and dimensions of of defects in diamond scribing depend on shape of diamond tip, the scratching direction, the moving velocity of the diamond tip, and applied scribing force.

We used n-type diodes and n-type strip sensors for our investigation. The strip sensors are position-sensitive radiation detectors. Modern radiation detectors are based on high-voltage semiconductor devices working in a full depletion mode. The basic operation is similar to a photo detector. The radiation hits the detector and generates charge carriers which are then collected on either top or bottom surface of the device. In order to achieve good charge collection from the full depth of the detector, voltages up to several thousands volts are applied. Since radiation detectors are operated under full depletion, their performance is very sensitive to the quality of their

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sidewalls, making radiation detectors ideal test structures for dicing-induced damage evaluation (low damage dicing).

2. Micro-fabrication

The goal of our fabrication method is to use full or partial silicon wafers. Hence, we need to use only post-processing micro-fabrication steps. (Some of our developments could be transferred to the pre-processing step.) Post-processing requires that all process temperatures must be kept below 400 °C, in order to protect the metalization.

We characterize the processed sensors by their leakage currents (or sometimes called dark or quiescent current) under reverse bias. The acceptable leakage current for radiation detectors that are used for high-energy physics (HEP) experiments have leakage currents <1 μA per cm^2. After cleaving the sidewall is passivated. The type of passivation depends on the substrate doping: (i) p-type silicon requires a sidewall passivation with a negative interface charge and (ii) n-type silicon a positive interface charge. In earlier studies we found, that ALD (atomic layer deposition) alumina, Al_2O_3, as passivation with a negative interface charge and PECVD (plasma enhanced chemical vapor deposition) silicon nitride, Si_3N_4, with a positive interface charge show the lowest leakage currents [8]. Similar passivations have been used to increase carrier life time for solar cells [9,10]. This paper only deals with n-type devices, so silicon nitride passivations were used.

HEP sensors work in harsh radiation environments. The sidewall passivation needs to be radiation hard which means that the interface retains a low trap density and its fixed charge. We are currently irradiating silicon nitride and alumina passivations for p- and n-type sensors. We will measure the leakage currents after the cool-down period and publish the results.

The n-type diodes were made by Hamamatsu Photonics K.K. (HPK) in Japan for the Fermi Gamma-ray Space Telescope. The devices were 400 μm thick and fully deplete at around 180 V. We also processed large area strip sensors from the Fermi mission. A strip detector is a segmented radiation detector. The sensor size was 3 cm × 3.5 cm, 128 strips and 194 μm pitch. These sensors have all the features of the full-size Fermi detectors. The device thickness and depletion voltage is the same as for the n-type diodes. (The same technique can be used for p-type silicon device but the type of sidewall changes [8].) All devices had a silicon oxide (SiO_2) surface passivation. The oxide layer was locally removed for the etch-scribing. The diamond- and laser-scribing was done with the top passivation.

2.1. Scribing

We used three different ways to scribe the silicon prior to cleaving: diamond-, laser, diamond-, laser-, and Xeon difluoride (XeF_2) etch-scribe (using XeF_2), see details below. The actual cleaving was done using a Dynatex GST-150 and a LSD-110 from Loomis Industries Inc.

2.1.1. Diamond-scribing

The diamond scribing was done using the GST-150 and LSD-110. Both system have scribe- and break capabilities. The diamond scribe lines were placed parallel to the edges of diodes and the strips. Fig. 1 shows an SEM (scanning electron microscope) micrograph from a diamond-scribed diode. The depth of the scribe is about 2 μm. Since these sensors have a SiO_2 surface passivation, two scratching passes were used. The first one breaks the passivation layer, and the second pass scribes the silicon surface.

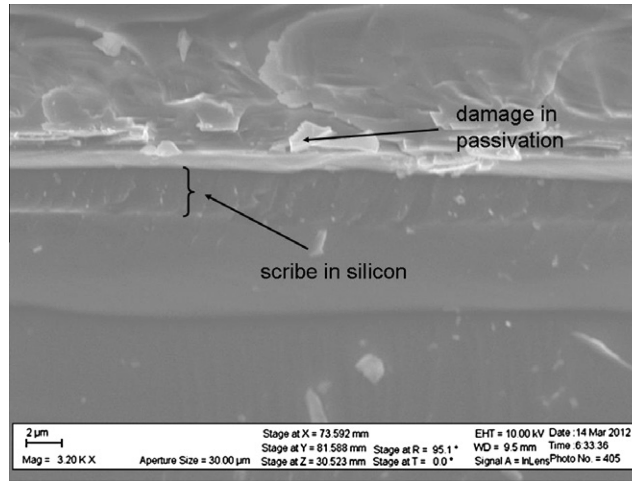

Fig. 1. SEM micrograph of a diamond-scribed sensor's sidewall after cleaving, the scribe depth is about 2 μm, chipping at the edge of the passivation layer is visible.

2.1.2. Laser-scribing

We used a commercial Oxford Laser E-Series micro-machining system with a diode-pumped solid state, frequency tripled Nd:YAG laser (355 nm wavelength) for laser-scribing. The laser pulse energy (power) and frequency were set at 10 mJ and 10 kHz, respectively. The diode pumping current was 36 A and the scan speed 1 mm/s. Fig. 2 shows an SEM micrograph of a laser-scribed silicon sensor (cross-section). The introduced laser-damage is clearly visible.

2.1.3. XeF_2 Etch-scribing

Dry etching techniques have been used for releasing sensitive MEMS devices. Overstolz et al. used a deep reactive ion etching (DRIE) to release MEMS devices on a SOI wafer [11]. The DRIE etch stopped at the buried oxide interface. An HF (hydrofluoric acid) vapor etch releases devices from the SOI carrier by under-etching the buried oxide. Panasonic Corp. developed a full dry etch system, Plasma Dicer PSX800, that etches silicon with an ICP (induction coupled plasma) [12]. The wafer is cut/etched with a SF_6/O_2 gas mixture. This gas mixture allows for an anisotropic through-etch. We, on the other hand, only scribe the silicon by a vapor etch step and do not fully release the devices by dry etching. We used a XeF_2 etch step to fabricate a scribe line parallel to the silicon strips. XeF_2 etching is very selective and does not introduce any silicon dam-

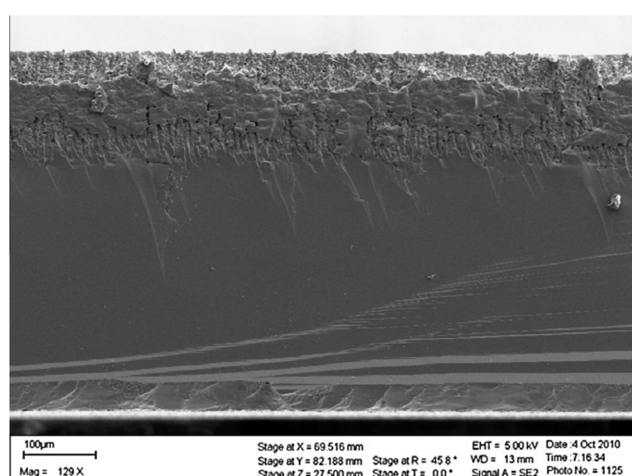

Fig. 2. SEM micrograph, cross section, laser-scribed sensor with laser-damage at sidewall (substrate thickness 400 μm) after cleaving.

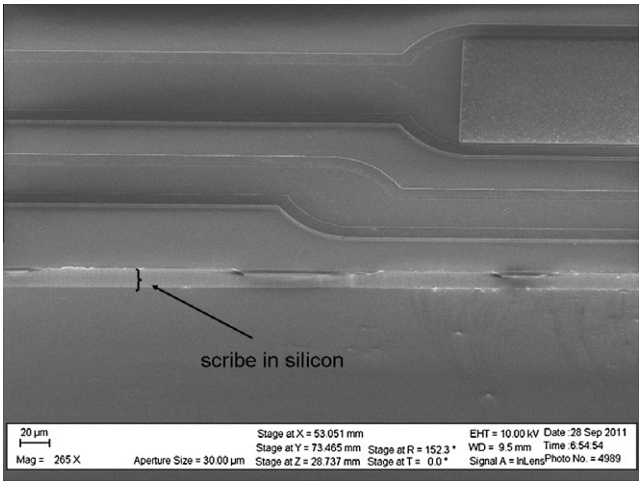

Fig. 3. SEM micrograph, bird's eye view, the XeF_2 etched groove is visible, the cleaved sidewall has almost no damage, no chipping of the passivation layer.

age. It is well suited for processing silicon sensors with existing metalization and surface passivations. A simple lithography step was used to define the scribe location. The typical etched scribe lines were 5 μm deep and 10 μm wide. Fig. 3 shows an optical micrograph and SEM micrograph from a sensor before and after cleaving. There is no visible damage at the cleaved part of the sidewall. We used a Xetch-3 from Xactic, Inc (20 etch pulses, one pulse at 1 mTorr XeF_2 and 30 mTorr nitrogen for 30 s). Fig. 3 shows a bird's-eye-view SEM micrograph of a cleaved sensor with a XeF_2 scribe line. The silicon sidewall underneath the shallow etched groove shows no visible damage.

2.2. Post-cleaving sidewall etch

We have used laser-micromachined holes in silicon as vertical electrodes and found that the leakage currents of the devices can be reduced by etching away the heat-affected silicon [13]. Heinze et al. used a fluorine plasma etch to recover the mechanical die strength after blade- or laser-dicing [14]. The rough sidewall after blade or laser-dicing increases the risk for mechanical fracture. In contrast to Heinze et al., we focus on the electrical properties of the dies not the mechanical ones.

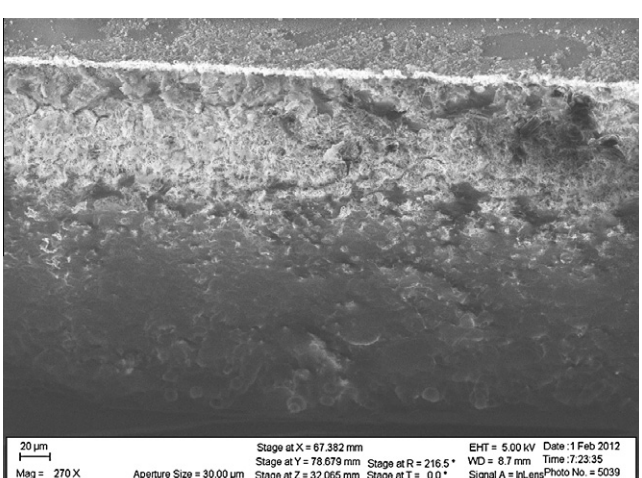

Fig. 4. SEM micrograph, bird's eye view, after laser-scribing and cleaving the sensor's sidewall was XeF_2 etched leading to visibly reduced laser-damage.

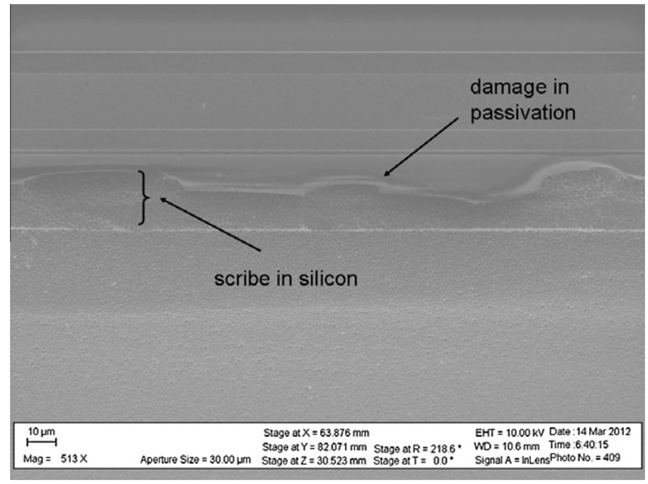

Fig. 5. SEM micrograph from a diamond-scribed sensor with XeF_2 sidewall etching.

Since we are using laser-scribing, there will also be a heat-affected zone. We use a XeF_2 etch with an etch depth of roughly 7 μm to remove the damaged silicon. Xeon difluoride has been used by Li et al. for mechanical die strength enhancement [15]. Since XeF_2 is very selective, no photo-resist mask was used. The sensor was just placed into placed into the Xetch-X3 XeF_2 gas etcher. The etching conditions were the same as for the etch-scribing. Fig. 4 shows an SEM micrograph of the sidewall from a laser-scribed sensor with a post cleaving XeF_2 etch. We estimate a 4 μm thick heat affected zone that is removed by a 7 μm deep etch. Since the laser also roughens the silicon, the roughness can not be removed by the XeF_2 etch step. The remaining roughness is clearly visible in Fig. 4.

We also applied the post-cleaving etch step to diamond-scribed diodes. Fig. 5 shows an SEM micrograph. The original scribe line is visible but smoothened by the etch step. The XeF_2 etch step does introduce some roughness at the sidewall, however it is much less than the roughness caused by saw or laser dicing.

2.3. Sidewall passivation

After cleaving, the sensors were placed in a Silox Vapox III etch solution (purchased from Transene, Inc.) for 10 s before alumina and nitride deposition. This HF (hydrogen fluoride) based etch ensures a hydrogen terminated side wall and removes any native silicon oxide on the sidewall. Silox Vapox III does not attack any active structures of the sensors (e.g. aluminum metalizations).

We used an Oxford Instruments PECVD (plasma enhanced chemical vapor deposition) system for the sidewall passivation. The chamber temperature was 300 °C. The nitride films were deposited using a mixed RF- and LPCVD method; the achieved film thickness is 100 nm. Since PECVD is not as conformal as ALD, we used a special holder that allowed for a sideway deposition onto the cleaved sidewalls.

After PECVD depositions, a RIE (reactive ion etch) step removed any excess material from the top surface of the sensor. A hard mask was used to preserve the deposition on the sides of the device. After RIE etching, the sensors were annealed at 400 °C. The annealing step helps to anneal any damage induced by the RIE etching step.

3. Experimental results and discussion

The fabricated sensors were evaluated based on their leakage currents. We measured the leakage currents of the different sensors using a probe station at room temperature. The IV curves were collected by using a Keithley 237 high voltage source measurement unit. The leakage current for the diodes was measured at the contact directly. The leakage currents shown for the strip sensors were measured at the bias ring, which surrounds the active sensor area. The bias ring is surrounded by one guard ring and provides the biasing voltage for all strips.

3.1. Diamond-scribing

The first technique we tested was diamond-scribing and cleaving. Diamond-scribing was rather common for separating silicon dies in the 1970s until blade-dicing become the dominant technique [16]. During diamond-scribing the diamond-tip locally deforms the silicon and forms a groove. Cracks inside the silicon form. Furthermore, diamond scribing has the potential to generate silicon debris. If the cracks reach the silicon surface, chipping occurs. Oliver et al. systematically studied diamond-scribing for MEMS die singulation [17]. Oliver et al. also show that the crack is a function of the scribing force. Cracks can reach from a few to dozens of micrometers into silicon depending on the used force. In comparison, the damage from standard blade dicing is normally over 100 μm deep [18].

3.2. Diamond-scribing post-cleaving sidewall etch

Since a damaged silicon sidewall leads to an increased leakage current and diamond-scribing will result in cracking and chipping, a XeF_2 etch was done to remove some of the damaged silicon. Fig. 6 shows IV curves for an n-type diode before and after the post-cleaving sidewall etch step. The leakage current was reduced. For comparison Fig. 6 also shows a scored and cleaved sensor. The scribe line was placed far outside the active area. (This method is same as the technique that produces mirror-like sidewalls for III–V laser-diodes.) When the device was cleaved the cleavage extends parallel to the active area. The curve labeled "scored and cleaved" effective shows the IV of a sensor without any sidewall damage because no scribe line was near the active area.

3.3. Laser-scribing

Fig. 7 shows the leakage currents for different strip sensors as function of the distance from the laser-scribe/cut line to the guard ring. The laser-scribe was roughly 15–20 μm deep for all shown

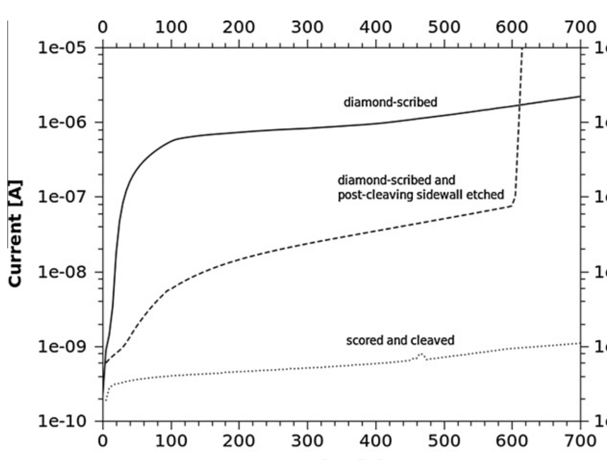

Fig. 6. IV curves for n-type diodes that were (i) diamond-scribed, (ii) diamond-scribed and sidewall etched, (iii) a scored and cleaved.

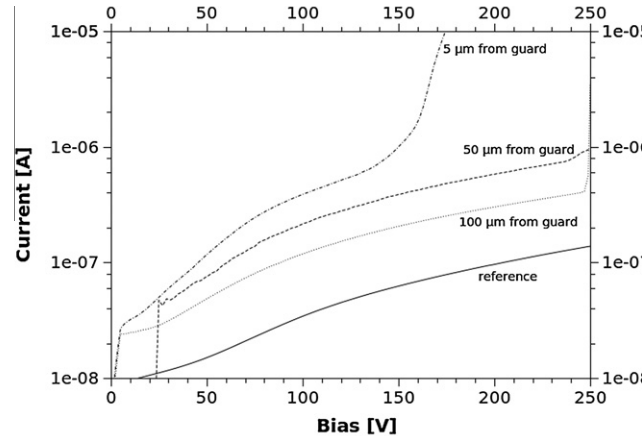

Fig. 7. IV curves for different laser-scribed and cleaved n-type strip sensors. The leakage current depends on the distance from the edge to the guard ring. The reference is taken from a sensor on an un-cut wafer.

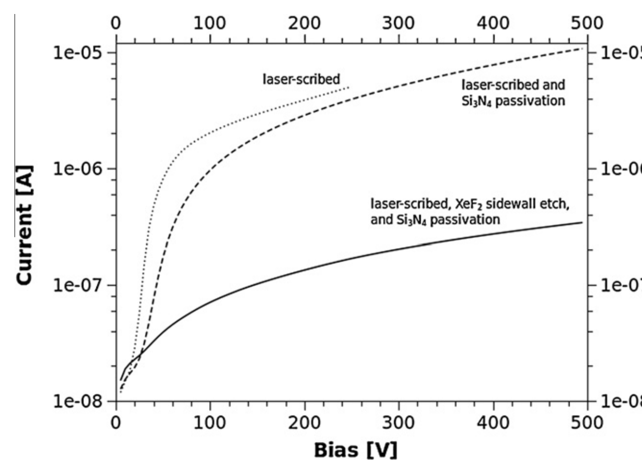

Fig. 8. IV curves, cut distance from the edge to the guard ring was 100 μm. A nitride sidewall passivation slight lowers the leakage current but a XeF_2 sidewall etch after cleaving in combination with a nitride sidewall passivation shows a dramatically reduced leakage current.

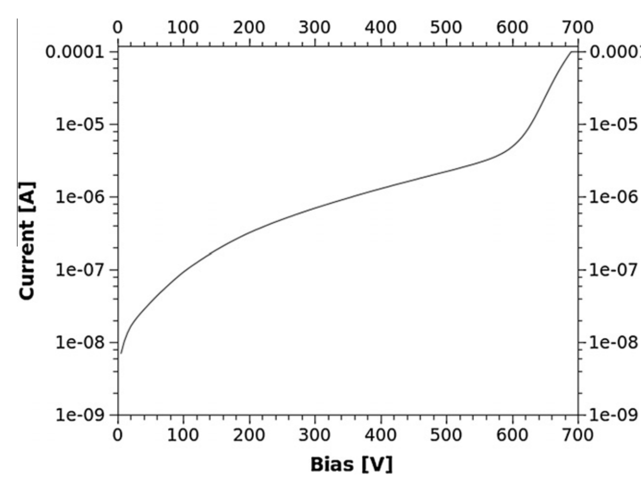

Fig. 9. IV curve from XeF_2-scribing and cleaving with silicon nitride passivation.

samples. The leakage current decreases as the cut distance increases. The sensor with a distance of only 5 μm shows a rather high leakage current. Since laser-scribing introduces sidewall

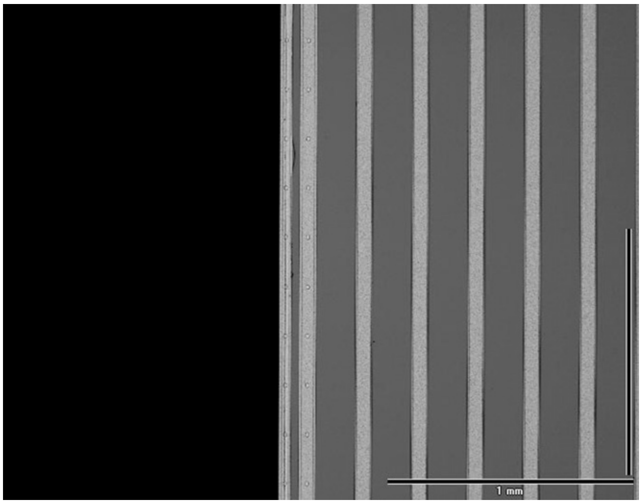

Fig. 10. Optical micrograph, top-view, sensor after XeF_2-scribing and cleaving, the cut was place at the edge of the guard ring.

damage, the closer this damage is placed towards to active area of the devices the higher the resulting leakage current is.

3.4. Laser-scribing post-cleaving sidewall etch

Fig. 8 shows the effect of the post-cleaving sidewall etch with XeF_2. The laser-scribe line for all sensors was roughly 100 μm deep and the distance from the cut to the guard ring was 90 μm. Fig. 8 shows that a sidewall passivation reduces the leakage current slightly. The post-cleaving sidewall etch prior to passivation reduces the leakage current significantly. The etch step removed some laser-introduced damage, resulting a lower leakage current.

3.5. XeF2-scribing

Fig. 9 shows an IV curve from a sensor that was etch-scribed. The XeF_2-etched groove was place right at the edge of the guard ring, see Fig. 10 for an optical micrograph. Although the edge is right at the guard ring, the leakage current is rather low. Especially, when one compares these results with the leakage currents from the laser-scribed sensors. As shown in Fig. 3 there is no sidewall damage. At full depletion, 180 V, the leakage current is <0.5 μA per cm^2, making this a usable sensor for a HEP (high energy physics) experiment.

4. Summary

Scribing and cleaving is not commonly used for separating silicon dies, other than MEMS devices. We used scribing and cleaving for dicing silicon radiation detectors. We found that the leakage current, a measure of the sidewall quality, is a function of the damage on the sidewall, cut distance to the guard ring, and sidewall passivation. The lower the sidewall damages the lower the leakage current. An etch-scribed sensor has very low sidewall damage. Furthermore, a post-cleaving etch can be used as post-cleaving step to remove sidewall damage. These advances are also relevant for other silicon devices requiring bulk depletion; examples are fully depleted CCDs [19] or any application where the silicon edge quality is important.

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