Leakage current of amorphous silicon \( p-i-n \) diodes made by ion shower doping

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In this letter, we report the leakage current of amorphous silicon (\( a\)-Si:H) \( p-i-n \) photodiodes, of which the \( p \) layer is formed by ion shower doping. The ion shower doping technique has an advantage over plasma-enhanced chemical vapor deposition (PECVD) in the fabrication of a large-area amorphous silicon flat-panel detector. The leakage current of the ion shower diodes shows a better uniformity within a 30 cm \( \times \) 40 cm substrate than that of the PECVD diodes. However, it shows a higher leakage current of \( 2-3 \) pA/mm\(^2\) at \(-5\) V. This high current originates from the high injection current at the \( p-i \) junction. © 2002 American Institute of Physics.

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Flat-panel detectors using amorphous silicon technology have been developed for x-ray imaging applications.\(^1,2\) A detector consists of a pixel array coupled to a scintillator and peripheral electronics. Each pixel on the detector consists of an \( a\)-Si:H \( p-i-n \) photodiode connected to an \( a\)-Si:H thin-film transistor (TFT). The photodiode has a good quantum efficiency in visible range and the peak of 80\%–90\% in optimized diodes occurs in the range 500–600 nm.\(^3\) The general method for fabricating \( a\)-Si:H diode is plasma-enhanced chemical vapor deposition (PECVD). In the PECVD method, silane gas and other added gases for doping are decomposed by the plasma and grown on a glass substrate. \( p\) - and \( n\)-type \( a\)-Si:H layers can be obtained by adding dopant gases such as diborane (\( B_2H_6 \)) or phosphine (\( PH_3 \)). In this study, we used an ion-shower doping method to form the \( p\)-layer of \( a\)-Si:H \( p-i-n \) diodes. We choose this method for two reasons. First, diodes made by conventional PECVD showed poor uniformity of leakage current in a large-area substrate. Among the components of the leakage current, the injection current seems to be the major cause of the poor uniformity. Second, when we fabricate a TFT array only for an active matrix liquid crystal display (AMLCD) application, no boron doping is required. However, diode fabrication requires boron doping, which may contaminate the PECVD chamber and affects the TFT deposition process. Since the ion-shower doping is performed in another process chamber, it does not result in boron contamination of the PECVD chamber and it may provide high reproducibility of the photodiode leakage current. A reduction of bad pixels is expected as well.

For the source and drain doping of TFT in large-area processing, an ion shower doping technique was used instead of conventional ion implantation techniques.\(^4\) The ion shower doping system, which consists of ion generation and ion acceleration components, has no mass separation and no beam scanning. The ions are diffused from the plasma region into the acceleration region where they are accelerated by a potential difference between grids, and then irradiated onto the samples. The ion-shower doping is similar to ion implantation, in which the ion beam is extracted from the discharge chamber and irradiated onto the substrate. Hence, this method has nonmass selectivity and large area implant capability. It differs from ion implantation, however, in that grids are placed between the plasma source and substrate to extract and accelerate the ions from the plasma, instead of using a substrate bias.\(^5\)

We made amorphous silicon \( p-i-n \) diodes on a 30 cm \( \times \) 40 cm substrate using four different masks, and each diode has the cross-sectional structure shown in Fig. 1. After Cr is deposited with a thickness of 150 nm on a glass substrate, 50-nm-\( n \) and 1000-nm-\( i \) layers are successively deposited by PECVD. A 50-nm-\( p \) layer is then formed by ion shower doping. \( B_2H_6/H_2 \) plasma ion shower doping is performed at an acceleration voltage of 20 kV and an ion dose of \( 8 \times 10^{16}\) cm\(^{-2}\). In ion shower doping a boron ion beam penetrates an intrinsic layer and forms a \( p\)-layer. Consequently, the intrinsic layer thickness becomes slightly shorter, and the \( p\)-layer thickness is estimated to be 50 nm from the boron doping profile. Ohmic contacts to the sensor are formed by a 150 nm layer of chrome underneath the lower doped layer and by a 60 nm layer of the transparent conduction material, indium tin oxide (ITO), above the upper doped layer. The

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![FIG. 1. Structure of \( a\)-Si:H \( p-i-n \) diode.](image)
films are then etched in the sequence of ITO/p/i/n. Finally, a silicon nitride passivation layer with a thickness of 450 nm is coated on the whole film, and contact metal is sputtered.

The leakage currents of the diodes were measured using an HP4155 semiconductor parameter analyzer, and all the measurements were performed in an electronically shielded dark box. After a negative bias is applied, the transient current showed monotonic decay or rise after decay to an asymptotic value. We determined the steady value as a leakage current at that bias. Figure 2 shows the selected leakage current of ion-shower diodes and PECVD diodes previously fabricated as a function of reverse bias. Each diode has the same area of 1 mm² and they are diagonally distributed over the whole substrate. At −5 V, which is conventionally used in flat-panel detectors, the average leakage current of ion-shower diodes is $2.487 \times 10^{-12}$ A/mm² and that of PECVD diodes is $7.693 \times 10^{-13}$ A/mm². The ion shower diodes show a higher leakage current than the PECVD diodes. However, ion shower diodes show good uniformity of leakage current within the same substrate. The standard deviation of leakage current of ion shower diodes is $2 \times 10^{-14}$ A/mm² for 30 different samples, which is evenly sampled on the substrate. For PECVD diodes, it is $4 \times 10^{-11}$ A/mm². This good uniformity is an advantage in the fabrication of large-area devices.

The leakage current as a function of time after bias application is shown in Fig. 3. At −5 V, the leakage current of the PECVD and ion-shower diode show monotonic decay to a steady-state value. At −10 V the ion shower diode shows different behavior. It decays initially, and then rises up to an asymptotic value. This behavior is similar to the high injection current behavior previously reported for a-Si:H p-i-n diodes and Schottky diodes. Amorphous silicon has many defects within a band gap and defects are strongly related with the leakage current. The current decay in Fig. 3 is due to the release of excess charge trapped in metastable defect states, and steady state current is maintained by the thermal excitation of electrons from the valence band to the conduction band. Since the forward-bias characteristics show no variation among the samples, we conclude that the injection current is from contact property. If a junction has a high potential barrier and small defects, the injection current is smaller than the bulk generation. However, if the potential barrier at the p–i interface decreases up to a certain amount and trap centers in the band gap near the junction increase, the injection current can become more dominant over the bulk generation current at high bias. This causes a rise in transient current at high bias.

We found the ion shower diode has a poor contact junction from the secondary ion mass spectroscopy (SIMS) measurements. The SIMS measurements shown in Fig. 4 were performed to investigate the junction property. The boron concentration is quantized accurately using a reference boron sample, and the silicon measurements indicate just a count
number of secondary ions. The boron concentration of the ion-shower diode near the $p-i$ interface approximates a Gaussian distribution that usually appears in the dopant profile of the ion implantation. The Gaussian boron profile brings the Fermi level closer to the center of band gap, and it lowers the potential barrier at the interface, as shown in Fig. 5. This increases the thermal enhanced injection and hopping current via trap centers at high bias. Consequently, as a result of the high injection current, the ion shower diode shows a high leakage current. We expect that multiple ion shower doping using different energies and doses to make a flat contact junction would lower the injection current.

In summary, we made amorphous silicon photodiodes based on ion shower doping, and measured the steady state and transient leakage currents. The diodes have a leakage current of 2 – 3 pA/mm² at –5 V and shows good uniformity of the leakage current within a same substrate. However, the magnitude of the leakage current is higher than that of a conventional PECVD diode. This high current originates from the high injection current at the $p-i$ junction.

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