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Surface passivation of InAs avalanche photodiodes for low-noise infrared imaging

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Abstract—The effect of surface passivation on the etched-mesa InAs diodes was investigated by carrying out the fabrication and passivation of InAs diodes. Extensive and detailed current-voltage characterization was done to determine the most suitable type of insulating material for the surface passivation. SU-8, silicon nitride, silicon dioxide and B-staged Bisbenzocyclobutene were used for the purpose of minimizing the conductivity of the etched mesa surface of InAs diodes. The forward- and reverse-biased characteristics of InAs diodes were measured at room temperature and 77 K in order to carefully investigate the effect of different surface passivation schemes. The results of this work categorically indicated that SU-8 is the most effective surface passivation material for InAs diodes, whereas silicon nitride and silicon dioxide have contributed to an even higher surface leakage current. Furthermore, SU-8 passivated InAs diodes were more sustainable to high bias voltages and its robustness increases the opportunity of its utilization for practical applications such as infrared imaging.

Index Terms—Avalanche photodiodes, InAs, infrared imaging, leakage current, surface passivation

I. INTRODUCTION

THE initial research and development of avalanche photodiodes (APDs) were primarily focused on design of high bit-rate receivers for long haul optical fiber communication [1]. Further work and characterizations of APDs with different types of semiconductor materials have discovered the potential of APDs in other applications which require highly sensitive photodetectors such as long range active imaging [2], infrared (IR) camera, gas sensing and X-Ray detection [3]. This is largely due to the capability of APDs in providing avalanche gain that is able to improve the overall system sensitivity or signal to noise ratio, when the APDs are incorporated into a detection system with an external signal amplifier.

One of the popular applications of APDs is the infrared imaging as this imaging and detection technique is very useful for temperature sensing, long-range and night vision, biometric verification and gas sensing. Due to its narrow bandgap energy which provides a cut-off absorption wavelength of ~3.6 μm at room temperature (~295 K), Indium Arsenide (InAs) APDs have gained attention from the researchers to carry out substantial amount of work in characterizing the leakage current [4], avalanche gain [5], excess noise [6], gain bandwidth product [7] and the temperature dependence properties [8] of InAs APDs. Further work was also carried out in fabricating InAs linear array detectors [9], fabricating InAs diodes using ion implantation technique [10] and increasing the avalanche gain of APDs at a particular bias voltage [11]. Throughout these characterization work, InAs APDs have consistently shown its ideal electron-APD (e-APD) characteristics, which is crucial in ensuring minimal noise at high avalanche gain. However, it was also identified that the high reverse-bias leakage current of InAs APDs may overshadow the valuable e-APD characteristics due to the high shot noise caused by the leakage current. This issue will be a major hurdle in employing InAs APDs for practical applications such as infrared imaging.

Bulk leakage and surface leakage are the 2 major contributors to the reverse-biased leakage current [4]. Bulk leakage current is mainly related to the quality of the semiconductor material, while the surface leakage current is due to the partially conductive etched-mesa surface. To overcome this issue, proper surface treatment using optimized insulating materials and procedures were needed. For instance, the dark current density of the SU-8 passivated type-II InAs/GaSb strained layer superlattice detectors [12] was reported to reduce by 4 orders of magnitude at 77 K, compared to the unpassivated devices.

Since the passivation of diode using SU-8 involves only spin-coating and UV exposure, the passivation technique can be incorporated easily into the fabrication process of InAs diodes. The passivation process also does not involve high temperature, which is crucial to avoid any possibility of contact diffusion and surface degradation. Therefore, SU-8 was used to passivate the InAs diodes in order to investigate the effectiveness of this dielectric material for surface passivation. Furthermore, in this work, a few commercially-used dielectrics such as silicon nitride (SiN_x), silicon dioxide (SiO_2) and B-staged Bisbenzocyclobutene (commonly referred to as BCB) were used to passivate InAs diodes and the effects of each passivation on InAs diodes were investigated and discussed.

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II. EXPERIMENTAL DETAIL AND RESULTS

Molecular Beam Epitaxy (MBE) and Metal Organic Vapor-Phase Epitaxy (MOVPE) are the two common techniques to grow InAs wafers. Due to its ability to produce high quality thick InAs wafers at a higher growth rate, MOVPE was used to grow InAs wafers for this work. Growth conditions were optimized at a growth temperature of ~ 600 °C. Since InAs is a narrow bandgap material in which ohmic contacts with metals can be easily achieved, the doping concentrations of the p- and n- cladding layers were controlled such that they were not unnecessarily high.

A. Fabrication and SU-8 passivation of InAs APDs

Before carrying out the optimization of the surface passivation to reduce the surface leakage current, the fabrication of diodes using wet chemical etching was carried out as reported by Marshall et al. [13]. Ti/Au of about 20/200 nm was deposited as the p- and n-contacts of the InAs diodes.

The freshly etched InAs n-i-p sample was cleaved into three pieces, one acting as the reference sample and the other two were passivated by SU-8 5.

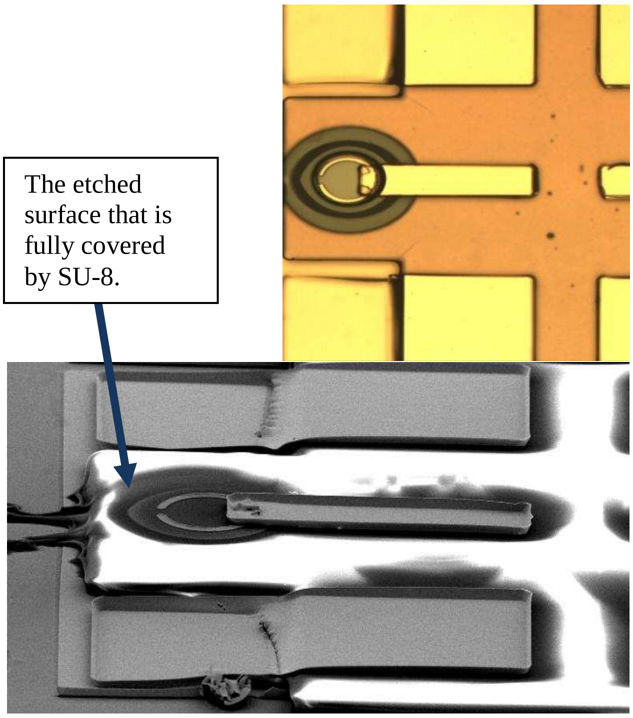

Fig. 1. A color image of the fabricated and surface-passivated InAs mesa-etched diode (top). The SEM image of the InAs diode (bottom) that clearly shows the etched-surface is fully covered and protected by SU-8

Fig. 1 shows the color image of the fabricated and SU-8 surface passivated InAs mesa-etched diode. The image obtained using the Scanning Electron Microscope (SEM) shows that the SU-8 has fully covered the etched surface of the InAs diode.

B. I-V characteristics of SU-8 passivated InAs APDs

The forward-biased current-voltage (I-V) characteristics of the InAs APDs were first measured to ensure that the junction formation and the ohmic contacts were in good conditions. Then the forward-biased I-Vs were fitted using the following empirical equation [14],

$$I_F = I_o\left[exp\left(\frac{qV_t - IR}{nk_BT}\right) - 1\right], \qquad (eqn. 1)$$

Where I_F is the measured forward-biased current, I_o is the saturation current, V_t is the total voltage drop across the diode, n is the ideality factor, k_B is the Boltzmann's constant, T is the temperature in Kelvin and R is the series resistance. The measured forward-biased I-V and the fittings of the I-V are shown in Fig. 2.

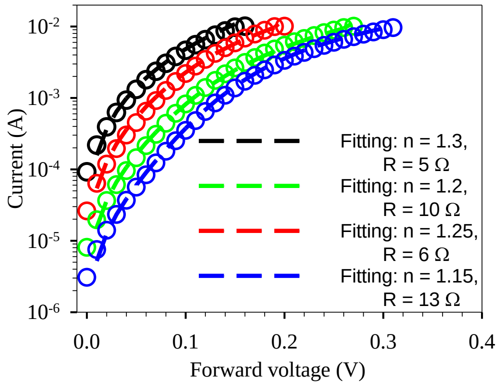

Fig. 2. The forward biased I-V characteristics of InAs diodes (symbol: circle) with different radii at 25 (blue), 50 (green), 100 (red) and 200 (black) µm and their respective I-V fittings (dotted lines).

From the empirical equation fittings, it was determined that the ideality factors for all the InAs diodes with different sizes are between 1.15 and 1.3, which is very close to 1, suggesting a good n-i-p junction formed and there is more diffusion current than generation-recombination current. The series resistance, mainly due to the contact between the metal and the semiconductor, is reasonably low at 5 to 13 **Ω**. It can be observed that the contact resistance is sufficiently low for most of the APD applications even without thermal annealing because InAs is a semiconductor material with narrow bandgap energy.

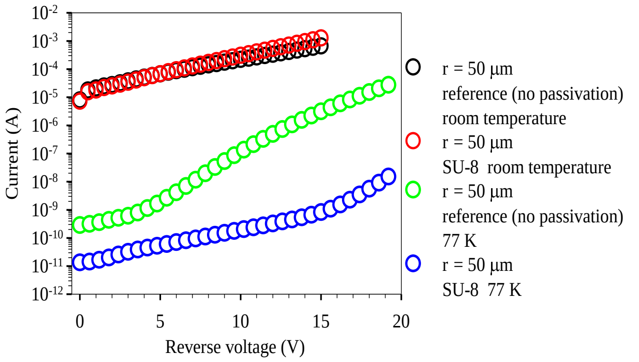

Fig. 3. The reverse biased I-V characteristic of the InAs 50-µm radius reference diode compared with those passivated by SU-8 with and without hard bake treatment at room temperature and 77 K.

The reverse-biased I-Vs or commonly known as the leakage current of diodes were then measured for all different sizes of InAs diodes. The room temperature and 77 K I-Vs of the reference and passivated diodes with 50-µm radius are shown in Fig. 3. Both samples exhibits very similar leakage current or dark current characteristics at room temperature. As the temperature decreases to 77 K, there is a clear difference in leakage current between these two samples. At low reverse-bias voltage of < 5 V, there is a reduction of ~ 2 orders of magnitude for the SU-8 passivated sample. At bias voltages > 15 V, the reduction in dark current for the SU-8 passivated sample is more obvious, approaching > 3 orders of magnitude. Therefore, there is a significant suppression of leakage current, mainly from the surface leakage current, when the InAs diodes are passivated by SU-8.

C. Effects of different surface passivations on InAs APDs

To study and investigate the difference between all the four passivation dielectric materials, namely SiO_2, SiN_x, BCB and SU-8, one big InAs sample was used for the fabrication of InAs diodes. To eliminate the possibility of surface degradation due to the fabrication and wet chemical etching, this sample was cleaved into 5 smaller samples just before the surface passivation was carried out. Each of them was passivated by SiO_2, SiN_x, BCB and SU-8 respectively while the last piece was left as the reference sample. Since they were all fabricated through exactly the same process before surface passivation, the difference in performance of diodes can be safely assumed to be mainly due to the different surface passivations.

The reverse-biased I-Vs of all the samples with 50-µm radius were measured at room temperature and presented in Fig. 4. The reference, SU-8 and BCB passivated InAs diodes show very similar leakage current levels at room temperature. However the SiO_2 and SiN_x passivated diodes have significantly high dark currents.

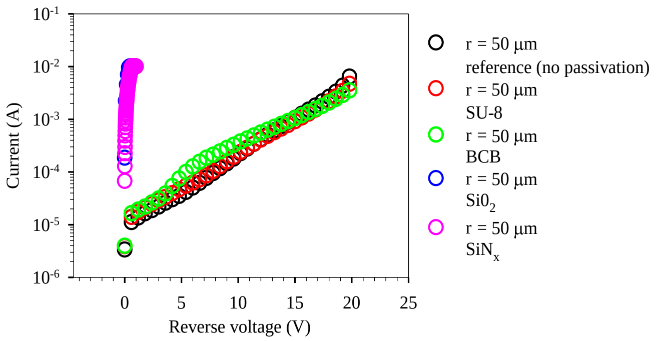

Fig. 4. The reverse biased I-V characteristic of a 50-µm radius reference diode, 50-µm radius diodes with SU-8, BCB, SiO_2 and SiN_x surface passivations at room temperature.

Besides having a lower dark current, the SU-8 passivated diodes are also more robust. They could be biased at higher bias voltages and showed consistent I-V characteristics after carrying out many times of I-V measurements. This feature will be critical when the InAs diodes are used in practical applications such as long range infrared imaging, where high gain and constant biasing of the diode are necessary.

III. CONCLUSION

From the fabrication, passivation and I-V characteristics of InAs diodes, the SU-8 dielectric has been identified as the most suitable dielectric for the surface passivation of InAs diodes. The study of the reverse-biased leakage current as a function of temperatures also clearly highlighted the effectiveness of SU-8 as a surface passivation dielectric. Furthermore, this passivation technique has also increased the robustness of the InAs APDs, which is especially crucial when higher and constant reverse biasing is needed for high avalanche gain applications.

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