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Influence of hydrogenation on the dark current mechanism of HgCdTe photovoltaic detectors

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Abstract: The influence of hydrogenation on the dark current mechanism of HgCdTe photovoltaic detectors is studied. The hydrogenation is achieved by exposing samples to a H_2/Ar plasma atmosphere that was produced during a reactive ion etching process. A set of variable-area photomask was specially designed to evaluate the hydrogenation effect. It was found that the current–voltage characteristics were gradually improved when detectors were hydrogenated by different areas. The fitting results of experimental results at reverse bias conditions sustained that the improvement of current–voltage curves was due to the suppression of trap assisted tunneling current and the enhancement of minority lifetime in the depletion region. It was also found that the dominative forward current was gradually converted from a generation–recombination current to a diffusion current with the enlargement of the hydrogenation area, which was infered from the ideality factors by abstraction of forward resistance–voltage curves of different detectors.

Key words: hydrogenation; passivation; dark current; photovoltaic detector; HgCdTe
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1. Introduction

HgCdTe photovoltaic (PV) detectors are the most used infrared sensors so far, especially in the fabrication of focal plane array (FPA) detectors. Due to the narrow gap of HgCdTe material, the surface and interface play a critical role in determining the performance of PV detectors. Different passivation techniques have been brought forward to improve the performance of detectors[1]. In the last decade, a novel method of hydrogenation for HgCdTe material and photodetectors has been studied by several research groups[2−9]. The passivation effects of hydrogenation in semiconductors are due to its ability to neutralize the shallow/deep charged impurities/defects[10]. For planar HgCdTe PV detectors made using the implantation technique, implantation-induced damage can easily be introduced and should be considered[11, 12]. The analysis of dark current mechanisms is often used to evaluate the performance of PV detectors[13]. As an effective passivation method, hydrogenation has found its ability in improving minority carrier lifetime and mobility[3, 7], reducing fixed interface charge density between ZnS and HgCdTe[4], and depressing $1/f$ noise of HgCdTe photodiodes[5]. This paper examines the effect of hydrogenation on the I–V characteristics and the inherent dark current mechanism of HgCdTe PV detectors by fitting the experimental results, and accordingly reckons hydrogenation as a convenient way to reduce the implantation damages that could deteriorate the performance of detectors.

2. Experimental details

The starting HgCdTe material was grown by a solid state recrystallisation (SSR) method. A vacancy doped p-type wafer of 2 cm in diameter was chosen for experiment, the Cd fraction of which is 0.3, and the Hall concentration and mobility of the hole at 77 K were 1×10^{16} cm^{-3} and 460 cm^2/(V·s) respectively. The wafer was cleaned using a standard organic clean process followed by an etching in 2% Br/Methanol solution. A 200 nm layer of ZnS was then thermally deposited at 1.6 Å/s with the temperature held below 70 ℃. The p–n junction was formed by B^+ implantation through the ZnS layer. After photolithography with a specially designed mask, the sample was exposed to a hydrogen/argon plasma during a reactive ion etch (RIE) for hydrogenation produced by an Oxford plasmalab 80 plus equipment. During the RIE process, the sample temperature held at 10 ℃. The total etching time was 15 min. The ZnS layer thickness after hydrogenation was about 120 nm. The photomask designed for hydrogenation is shown in Fig. 1, in which five elements of PV detectors were fabricated in an array. The No. 0 represents the element that is non-hydrogenated, and No. 1 is the element of which only n-type or implantation area is hydrogenated, and No. 2–No. 4 are the elements with hydrogenation area gradually enlarged. Then the array was patterned with In/Au using a lift-off process for electrical contacts. The final array was packaged into a cryogenic dewar for I–V

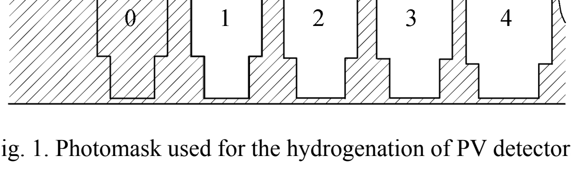

Fig. 1. Photomask used for the hydrogenation of PV detectors.

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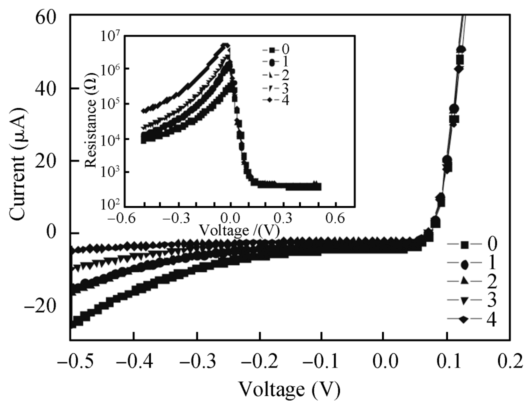

Fig. 2. Measured I–V and R–V curves for five elements.

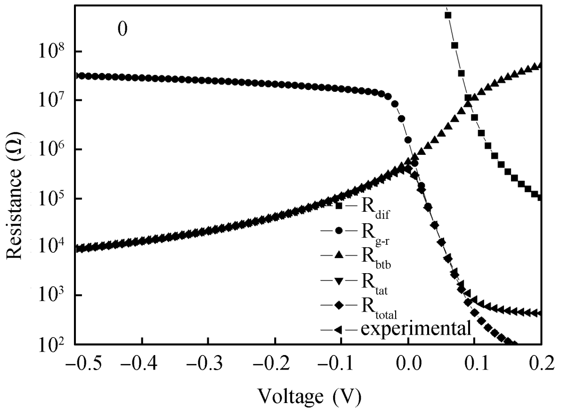

Fig. 3. Fitting result of No.0 element.

measurement at 77 K using a Keithley 236 instrument.

3. Results and discussion

The resulting I–V curves (Fig. 2) show an obvious improvement in the dark current while the hydrogenation area is gradually enlarged. As mentioned above, the analysis of the dark current mechanism is an effective means to evaluate the performance of PV detectors. In order to work more conveniently, the differentiate calculation was carried out for I–V curves, so the resistance–voltage (R–V) curves are obtained as manifested in the minor figure of Fig. 2. As discussed in Ref. [13], the dark current of a HgCdTe PV detector could be modeled as a combination of the current contributions due to the thermal diffusion of minority carriers from the quasi-neutral regions (I_{diff}), generation–recombination current in the depletion region ($I_{\text{g−r}}$), band-to-band tunneling current (I_{btb}), and trap assisted tunneling current (I_{tat}). So the dynamic resistance of R_{diff}, $R_{\text{g−r}}$, R_{btb} and R_{tat} for different dark current mechanisms could be given by a differentiate calculation and the total dynamic resistance R_{total} is given by

$$R_{\text{total}} = \left(\frac{1}{R_{\text{diff}}} + \frac{1}{R_{\text{g−r}}} + \frac{1}{R_{\text{btb}}} + \frac{1}{R_{\text{tat}}}\right)^{-1}. \tag{1}$$

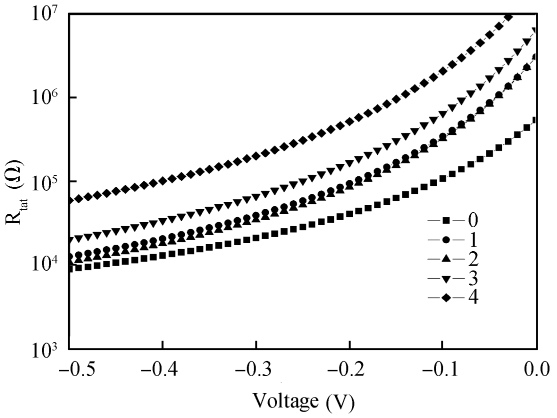

Fig. 4. Fitting results of R_{tat}

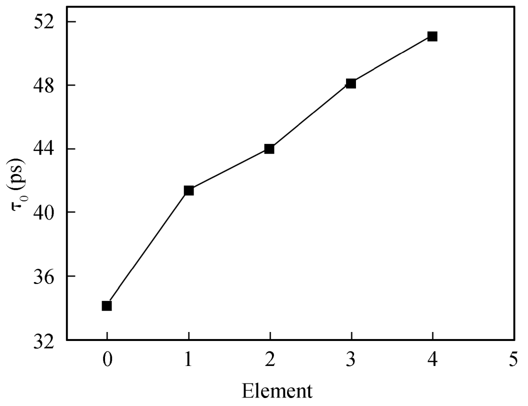

Fig. 5. Effective lifetime τ_0 in the depletion region.

To have a clear understanding of the influence of inherent mechanisms caused by hydrogenation, the dark current at forward and reverse biased conditions will be analyzed respectively. The latter was mainly contributed by $I_{\text{g−r}}$, I_{btb} and I_{tat}, and will be analyzed using the method described in Ref. [14]. Fitting processing and parameter determination were performed for R–V curves of five elements, and only the result of No. 0 element is shown in Fig. 3. It can be seen that at reverse biased conditions the dark current of the detector is dominated by the trap assisted tunneling current (I_{tat}). So the fitting results of R_{tat} for five detectors are shown in Fig. 4.

It can be seen that R_{tat} was obviously improved after different hydrogenations. This is especially reflected from the decrease of the dark current at larger reverse bias shown in Fig. 2. The impurities/defects in HgCdTe especially at the interface of ZnS/HgCdTe, a large part of which was caused by implantation damage, can play as trap centers to induce trap assisted tunneling current (I_{tat}). After hydrogenation many trap centers were passivated by hydrogen atoms or ions, and the bigger the hydrogenation area, the larger the extent of reduction for I_{tat}. As a result, R_{tat} was obviously increased with hydrogenation area. Another evidence of the improvement is the parameter of effective lifetime in the depletion region as denoted in Fig. 5, which were abstracted from the R–V curves. It is necessary to note that the increased extent of τ_0 for No. 1 element is much

Table 1. Ideality factors for five detectors.

Element	Ideality factor
0	2.01
1	1.52
2	1.5
3	1.5
4	1.3

larger than the other three. The difference among No. 1–No. 4 detectors is that only the implantation area was hydrogenated for No. 1. So it can be conferred that the implantation damages could be greatly decreased by the hydrogenation process.

The dark current at forward biased conditions mainly comprises $I_{\rm diff}$ and $I_{\rm g-r}$, and will be analyzed by the method of ideality factor abstraction. The forward I–V characteristics of these diodes can be expressed by the famous Schockley equation[15]:

$$I = I_0 \exp(qV/\eta kT), \tag{2}$$

where η represents the ideality factor. The other symbols in the equation have their normal meaning. While η is 1 and 2, the forward is dominated by diffusion current and generation–recombination current, respectively and an intermediate ideality factor ($1 < \eta < 2$) means comparable generation–recombination and diffusion contributions.

Table 1 shows ideality factors abstracted from the forward part of R–V curves for five detectors. It can be seen that the forward current is limited by generation–recombination current for the detector without hydrogenation. After the n-type area was hydrogenated, the ideality factor decreased greatly from 2.01 to 1.52, which means the reduction of generation–recombination centers and generation–recombination current after hydrogenation. While the hydrogenation area was gradually enlarged, the forward current was gradually converted to be dominated by diffusion current.

4. Conclusion

In summary, using a specially designed photomask, the influence of hydrogenation processing on the dark current mechanism of n-on-p PV detectors has been studied. By analyzing the dark current at reverse- and forward-biased conditions respectively, it was considered that hydrogenation can dramatically decrease the dark current through different mechanisms. It was also found that hydrogenation could be used to reduce the implantation damages, which could obviously deteriorate the dark current performance of PV detectors.

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