

Full Length Research Paper

An improvement of electrical characteristics of P-N diode by X-ray irradiation method

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This paper presents a new technique of semiconductor fabrication technology, where a soft X-ray annealing method is proposed as a new technique and used in this work. The effect of Pt and Soft X-ray annealing on P-N diodes was investigated. The tested P-N diodes were fabricated at TMEC laboratory using CMOS technology. Results obtained have shown that the platinum doping is affected both reverse and forward current characteristics of P-N diode, the leakage current is increased slightly, while the forward current is also increased 3 to 4 times, which is a result of reduction of carrier recombination lifetime of diode from 72 to 55 μ s. The characteristics of P-N diode after X-ray irradiation is improved significantly. There is a slight reduction of leakage current, whereas the forward current is increased about 3 to 4 order of magnitude. Furthermore, the recombination lifetime is decreased from 54 to 48 μ s.

Key words: Soft X-ray annealing method, P-N diode, forward current.

INTRODUCTION

P-N junction structures are widely used in many applications such as high switching diodes (Kuksenkov et al., 1997), oxygen sensors (Miller, 1976), power devices (Matsumoto et al., 2002), and optoelectronics devices (Wallgren and Sotiropoulos, 1999). Generally, a good diode should have low leakage current and high forward current (Poyai, 2002). However, P-N diodes can produce high leakage and low forward current due to defects during fabrication process. To further improve these properties, many researchers have tried to increase the performance of P-N junction diode. However, the performance target is always increased. Low performance characteristics of the diodes can have many reasons (Li et al., 2007; Li et al., 2011), where one of

them is the high energy ion implantation process. It is well-known that high energy ion implantation is essential for the fabrication of many devices. On the other hand, the ion implantation can introduce the damages which can bring dramatic effects on the diffusion of dopants, especially in the case of CMOS technology. Moreover, the Ion implantation process can cause the crystalline structure damage in a silicon bulk. However, it has been observed that the residual damage can be repaired by using a thermal annealing process (Williams, 1998; Felter et al., 2003; Moffatt et al., 2000; Bourdelle et al., 2001).

Generally, the effect of ion implantation process has caused the higher leakage current and lower forward current characteristics. In this paper, the focus will be on the forward current characteristics. Furthermore, the forward current is also of particular interest for improvement, in which the high responsiveness diodes with low power loss require high forward current. One of

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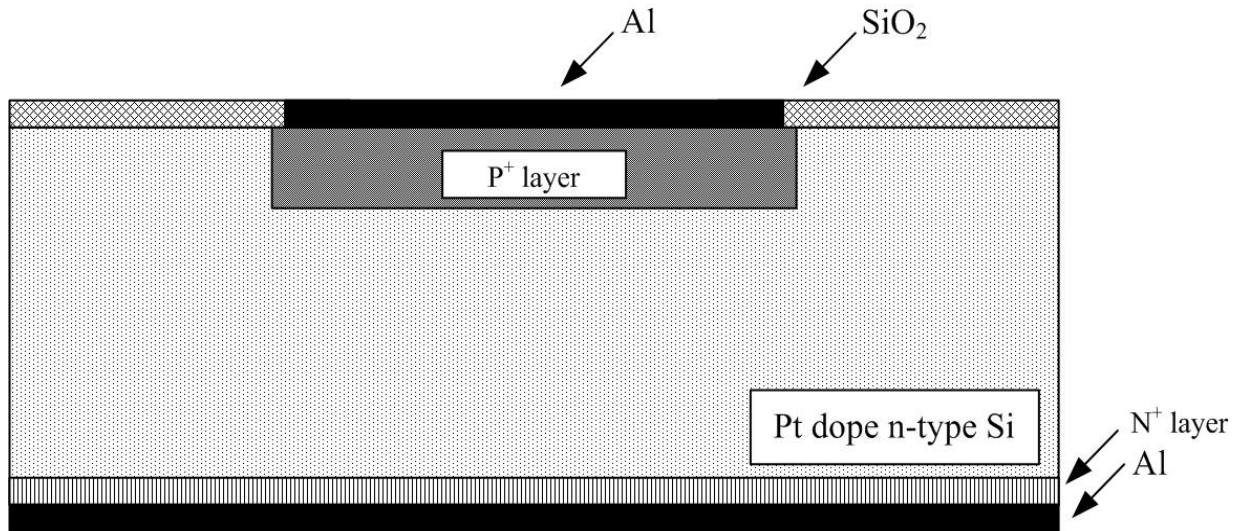


Figure 1. Device structure after fabrication.

the techniques for improving the forward current characteristics such as Pt-doping process is a popular technique to improving electrical characteristics of diode base on silicon. Pt-dope is extensively used in semiconductor device to improve the switching characteristics of the devices by decreasing the carrier lifetime. This, on the other hand, has the undesirable effect of increasing the material resistivity (Valdinoci et al., 1996).

As mentioned earlier, this technique has many associated problems that can decrease the performance of device. The Pt-dope technique can decrease the carrier lifetime but at the same time the series resistance of the diode can increase significantly (Miller et al., 1976; Williams, 1998; Ayyildiz et al., 1995). The series resistance is one of the important parameters in diode mechanism (Ayyildiz et al., 1995). At present, the damages from ion implantation process and Pt-dope are normally removed by thermal annealing technique (TAT). Although, TAT are widely used in many laboratories and industry, the performance of the device after TAT tends to be smaller than expected because some of the residual damages can be difficult to remove.

This paper presents a new technique for improving forward current characteristics of P-N diode. A soft X-ray annealing process was used for improving electrical characteristics of diodes. The soft X-ray irradiation is not widely used because few research works were done to confirm and find the appropriate X-ray energy ranges to be used in silicon based diode fabrication. An optimum X-ray energy and exposure time can be used to remove defects or damages in silicon devices [16]. The goal of this paper is to investigate the forward current of Pt-dope and undoped P-N diode, with various x-ray energy and exposure time.

METHODOLOGY

The P-N junction diode was fabricated with CMOS technology at Thai Microelectronics Center (TMEC) laboratory. For this study, P-N junction diodes were fabricated on the 325 μm thick n-type silicon substrate. The diode process module consisted of (i) deposition of silicon dioxide on the substrate, (ii) dry-etching of active area, (iii) implantation of boron at energy of 120 keV and dose of 1×10^{16} atoms/ cm^2 on the front side wafers (the implantation been followed by a thermal annealing at 1050°C for 60 min, resulting in a junction depth of about 1 μm), (iv) E-beam evaporation of Pt on the back side (v) thermal annealing at various temperatures between 850 and 900°C for 4 h, (vi) 1 μm thick Al deposition on the front and back sides. The final device is as shown in Figure 1.

The tested wafer was cut into the 4 mm^2 diodes that were measured to find their electrical properties. The results obtained were compared in both before and after X-ray irradiation at room temperature with various energy exposures of 55 and 70 keV and exposure time of 55 and 205 seconds (Sundarasaradula et al., 2011; Srithanachai and Niemcharoen, 2011). The semiconductor parameter analyzer, model HP4156B, was used to measure the electrical properties of diode, before and after irradiation. The current-voltage (I-V) characteristics of the P-N diode were measured at room temperature to examine the change of the dark current (I_D) by X-ray irradiation. The current-voltage (I-V) characteristics were measured on wafer with biasing step of 25 mV for both reverse (V_R) and forward (V_F) voltages.

RESULTS AND DISCUSSION

The electrical properties of P-N junction diode after Pt doping and X-ray irradiation are examined. Figure 2 shows the experimental result for forward and reverse-bias characteristics of the P-N junction diodes. The diode parameters are determined from the I-V characteristics, which usually describe using the thermionic emission theory. The ideal diode equation or sometimes called the Shockley diode equation is given by:

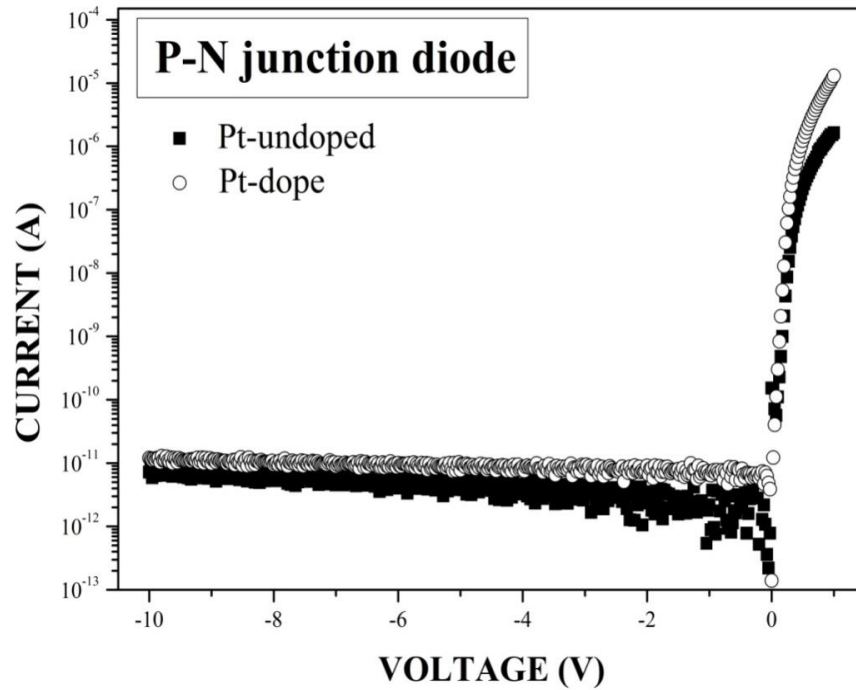


Figure 2. Semi-log I-V characteristics of P-N junction diode.

$$I = I_0 \exp(qV/nkT) - 1 \quad (1)$$

Where the saturation current (I_0) is equal to the diffusion current (I_d) (Poyai, 2002).

$$I_0 = I_d = qn_i^2 A [D_n/L_n N_A + D_p/L_p N_D] \quad (2)$$

Where I is the current, q is the electron charge, V is the applied voltage, T is the absolute temperature, k is the Boltzmann constant, n is the ideality factor of P-N diode, A is the active area, n_i is the intrinsic carrier density, and I_0 is the saturation current. For values of V greater than nkT/q , D_n and D_p are the diffusion coefficient of electrons in the p-side and holes in the n-side, L_n and L_p are the electron and hole diffusion lengths. The ideality factor from Eq. (1) can be written as described by Equation 3 (Keffous et al., 2003; Sahin et al., 2005).

$$n = [q/kT] [dV/d \ln I] \quad (3)$$

The voltage dependent ideality factor $n(V)$ can be written by using Equation 3 as:

$$n(V) = qv/[kT \ln(I/I_0)] \quad (4)$$

From Equation 1, I_0 is the saturation current. The saturation current under the reverse bias is the combination of the diffusion current (I_d), as presented in Equation 4.

The forward and reverse bias I-V characteristic of the P-N diode before and after irradiated by the various X-ray energy and times, which can be explained by Equation 5 (Schroder, 1997).

$$I = I_0 [\exp(q(V - IR_s)/nkT) - 1] \quad (5)$$

From Eq. (5) the effect of the series resistance is usually modeled with series combination of a diode and a resistor R_s . The voltage V_d across the diode can be expressed in terms of the total voltage drop V across the diode and the resistance R_s . Thus, $V_d = V - IR_s$ and the Equation 1 can be expressed as:

$$I = I_0 [\exp(q(V - IR_s)/nkT) - 1] \quad (6)$$

where q is the elementary charge, n is the ideality factor, k is the Boltzmann's constant, V is the biasing voltage, T is the temperature, R_s is the series resistance, and the IR_s term is the voltage drop across series resistance of device.

Several methods to extract the series resistance R_s of Schottky diode have been suggested. In our case, we have applied the methods developed by Cheung and Cheung (1986).

The Cheung's method is achieved by using the functions:

$$dV/d(\ln I) = IR_s - nkT/q \quad (7)$$

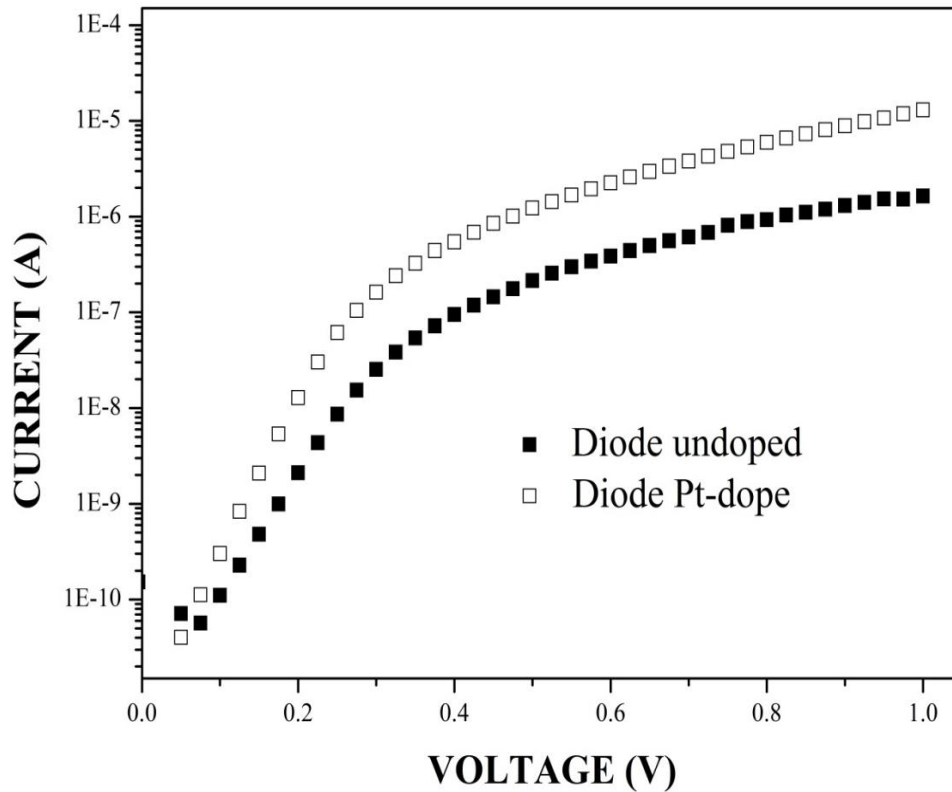


Figure 3. Improvement of forward current of the diode after Platinum dope.

Equation 7 should give a straight line for the data of the downward curvature region of the forward bias I-V characteristics. Thus, the slope and y-axis intercept of a plot of $dV/d(\ln(I))$ versus I will give R_s and nkT/q , respectively.

Figure 2 shows the current-voltage (I-V) characteristics of Pt-dope P-N diode, which is shown that the reverse and forward currents after Pt-dope were both higher than the original values. However, while the leakage current only slightly increased, while the forward current changed more significantly. Figure 3 shows the semi-log scale of forward current characteristics of P-N diode. The forward current increased about 3 to 4 times after Pt-dope. The carrier recombination lifetime of P-N diode after Pt diffusion process decreased from 72 to 55 μ s and the series resistance increased from 10 to 18 Ω . This is shown that that Pt could significantly affect the carrier lifetime and series resistance of P-N diode. Although, the trend of forward current was rising but it was still considered to be below the expectation value. At present, the thermal annealing technique is widely used for treating the performance of device after fabrication. However, it cannot completely remove some defects during the fabrication process such as damages from Pt diffusion, high energy ion implantation and defects from lithography process.

This work presents a new technique for improving the forward current of device on silicon substrate. The soft X-ray annealing method is the technique for improving the performance of the diode. Figure 4 shows I-V characteristics of P-N diode before and after irradiation by X-ray at various energy and exposure times. From Figure 4, it can be noted that the reverse currents reduced slightly, while forward current increased. An interesting observation was that the forward current after irradiation increased much more significantly than the purely Pt-dope process. Figure 5 shows the typical result of the diode before and after irradiation. Figure 5 shows that the forward current increased by about 3 to 4 orders of magnitude. Many researchers have investigated the effect of radiation to the devices based on silicon. However their performance degraded after irradiation with high energy electron, neutron and proton (Simoen et al., 2002; Ohyama et al., 2001; Czerwinski et al., 2002; Takakura et al., 2006). Therefore, this paper presents a new approach of using low energy irradiation to improve the diode's performance, in which the carriers lifetimes of P-N diodes are determined by using the I-V characteristics (Poyai et al., 2003; Poyai et al., 2001). From the experiment results, the recombination lifetime decreased from 54 to 48 μ s. The series resistances of diode after irradiation also decrease from 10 to 10 Ω . The

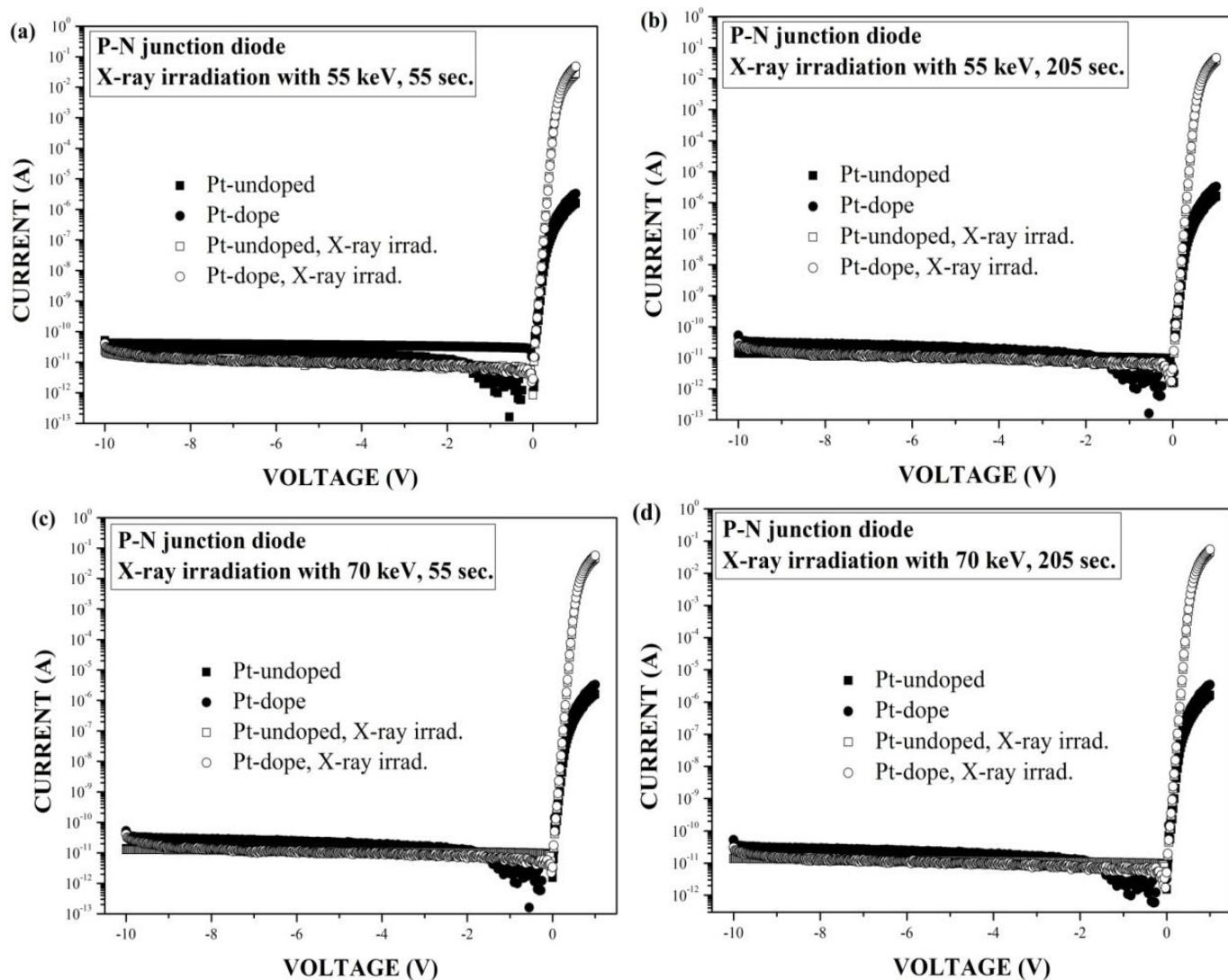


Figure 4. I-V characteristics after X-ray irradiation at different irradiation time and energy.

ideality factors of diode were not change by the value of 1, and the barrier height decreased from 0.95 to 0.9 eV, which is shown that soft X-ray annealing method can increase forward current and decrease series resistance.

Conclusions

The effect of soft X-ray annealing method was used to investigate the semiconductor fabricated samples and discussed. Results obtained have shown that the leakage current increased slightly after Pt-dope, while the forward current increased about 3 to 4 times. Pt-dope could also reduce the carrier lifetime, whereas the series resistance increased from the original value. The characteristics of diode after soft X-ray annealing process also increased. The leakage current slightly decreased. However, we

found that the forward current was increased by 3 to 4 orders of magnitude. The soft X-ray annealing technique could also reduce the recombination lifetime and series resistance of Pt-dope and undoped P-N diodes. In conclusion, the soft X-ray annealing is important technique to help the semiconductor industrial for improving device performance. This result is potentially important to the improvement of semiconductor device's performance for both semiconductor industry and other possible research avenues.

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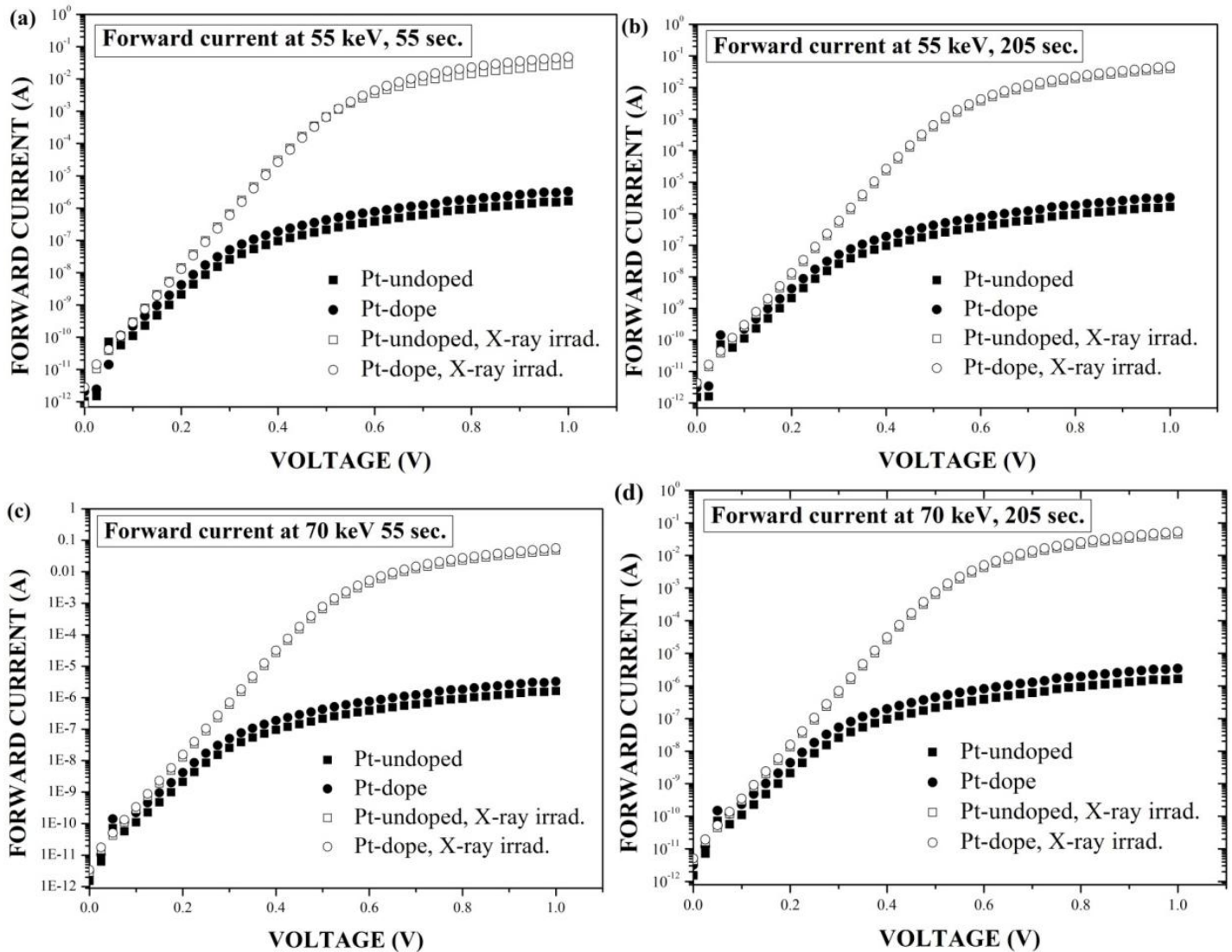


Figure 5. Forward current after X-ray irradiation of diode compares between dope and undoped Platinum.

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REFERENCES

- Ayyildiz E, Turut A, Efeoglu H, Tuzemen S, Saglam M, Yogurtcu YK (1995). Effect of series resistance on the forward current-voltage characteristics of schottky diodes in the presence of interfacial layer. *solid-state electronics*, 39: 83-87.
- Bourdelle KK, Chen Y, Ashton RA, Rubin LM, Agarwal A, Morris WA (2001). *IEEE Trans. Electron. Dev.*, 48: 2043.
- Cheung SK, Cheung NW (1986). Extraction of Schottky diode parameters from forward current-voltage characteristics. *Appl. Phys. Lett.*, 49: 85.
- Czerwinski A, Katcki J, Ratajczak J, Simoen E, Poyai A, Claeys C, Ohyama H (2002). Impact of fast-neutron irradiation on the silicon p-n junction leakage and role of the diffusion reverse current. *ucl. Instr. Meth. Phys. Res. B.*, 186: 166-170.
- Felter TE, Hrubesh L, Kubota A, Davila L, Caturla M. (2003). Laser damage probability studies of fused silica modified by MeV ion implantation. *Nucl. Instr. Meth. Phys. Res. B.*, 207: 72-79.
- Keffous A, Siad M, Mamma S, Belkacem Y, Chaouch CL, Menari H, Dahmani A, Chergui W (2003) Effect of series resistance on the performance of high resistivity silicon Schottky diode. *Appl. Surf. Sci.*, 218: 336-342.
- Kuksenkov DV, Temkin H, Osinsky A, Gaska R, Khan MA (1997). Low-frequency noise and performance of GaN p-n junction photodetectors. *J. Appl. Phys.*, 97: 759-762.
- Li J, Han L, Duan J, Zhong J (2007). Interface mechanism of ultrasonic flip chip bonding. *Appl. Phys. Lett.*, 90: 242902.
- Li J, Liu L, Deng L, Ma B, Wang F, Han L (2011). Interfacial microstructures and thermodynamics of thermosonic Cu-wire bonding. *IEEE Electr. Device. L.*, 10: 1433-1435.
- Matsumoto Y, Nakazono A, Kitahara T, Koike Y (2002). High efficiency optical coupler for a small photo acceptance area communication. *Sensors and Actuators A: Physical*, 97-98: 318-322.
- Miller MD (1976). Differences between platinum and gold doped silicon power device. *IEEE Trans. Electron. Dev.*, 23: 1279-1283.
- Miller MD, Schade H, Nuese CJ (1976). Lifetime-controlling

- recombination centers in platinum-diffused silicon. *J. Appl. Phys.*, 47: 275-279.
- Moffatt S, Hemment PLF, Whelan S, Armour DG (2000). Silicon damage studies due to ultra-low-energy ion implantation with heavy species and rapid thermal annealing. *Mat. Sci. Semicon. Proc.*, 3: 291-296.
- Ohyama H, Hirao T, Simoen E, Claeys C, Onoda S, Takami Y, Itoh H (2001). Impact of lattice defects on the performance degradation of Si photodiodes by high-temperature gamma and electron irradiation. *Physica B*, 308-310: 1226-1229.
- Poyai A (2002). Defect assessment in advanced semiconductor materials and devices, pp. 99-163.
- Poyai A, Simoen E, Claeys C, Rooyackers R, Badenes G (2001). Lifetime study in advance isolation techniques. *Mater. Sci. Semicon. Process.*, 4: 137-139.
- Poyai A, Simoen E, Claeys C, Gaubas E, Huber A, Graf D (2003). Extraction of the carrier generation and recombination lifetime from the forward characteristics of advanced diodes. *Material Sc & Eng. B.*, 102: 189-192.
- Sahin B, Cetin HC, Ayyildiz E (2005). The effect of series resistance on capacitance-voltage characteristics of Schottky barrier diodes. *Solid State Comm.*, 135: 490-495.
- Schroder DK (1997). Carrier lifetimes in silicon. *IEEE Trans. Electron. Dev.*, 44: 160-170.
- Simoen E, Claeys C, Privitera V, Coffa S, Kokkoris M, Kossionides E, Fanourakis G, Larsen AN, Clauws P (2002). DLTS and PL studies of proton radiation defects in tin-doped FZ silicon. *Nucl. Instr. Meth. Phys. Res. B.*, 186: 19-23.
- Srithanachai I, Niemcharoen S (2011). Influence of X-ray irradiated on junction depth of P-N diode. *The 5th PSU-UNS Int. Conf. Eng. technol.*, 1: 498-501.
- Sundarasaradula Y, Srithanachai I, Ueamanapong S, Atiwongsaengthong N, Poyai A, Niemcharoen S, Titiroongruang W (2011). Electrical characteristics of X-ray irradiation on PN diode, Electrical characteristics of X-ray irradiation on PN diode. *The 5th PSU-UNS Int. conf. eng. technol.*, 1: 461-464.
- Takakura K, Hayama K, Watanabe D, Ohyama H, Kudou T, Shigaki K, Matsuda S, Kuboyama S, Kishikawa T, Uemurac J, Simoen E, Claeys C (2006). Radiation defects and degradation of Si photodiodes irradiated by neutrons at low temperature. *Physica B*, 376-377: 403-406.
- Valdinoci M, Colalongo L, Pellegrini A, Rudan M (1996). Analysis of conductivity degradation in Gold/Platinum-doped silicon. *IEEE Trans. Electron. Dev.*, 43: 2269-2275.
- Wallgren K, Sotiropoulos S (1999). Oxygen sensors based on a new design concept for amperometric solid state devices. *Sensors and Actuators B*, 60: 174-183.
- Williams JS (1998). Ion implantation of semiconductors. *Mater. Sci. Eng. A.*, 253: 8-15.
- Williams JS (1998). Ion implantation of semiconductors. *Mater. Sci. Eng. B.*, 253: 8-15.