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AMORPHOUS SILICON (a-Si)/CRYSTALLINE SILICON (c-Si) DOUBLE HETEROJUNCTION X-RAY SENSOR

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With a full utilization of the low-temperature process of amorphous silicon (a-Si) thin-film deposition and long carrier-lifetime of high-purity crystalline silicon (c-Si), we have developed a new type of a-Si/c-Si double heterojunction X-ray sensor. The sensor has a structure of Au/p a-SiC/n c-Si/n a-Si/Al. High-purity NTD (neutron transmutation doping) crystalline silicon wafer was used as substrate. The high purity NTD crystalline silicon has a long carrier-lifetime (about 400 μ s), and the low deposition temperature of a-Si makes no adverse effects on the carrier lifetime. Therefore, large photogenerated carrier collection efficiency and high sensitivity can be obtained.

The characteristics of this kind of X-ray sensor have been examined. The linear relationship between output current and X-ray intensity is good, and the sensitivity is high. This kind of X-ray sensor can be used under zero-bias condition. The zero-bias operation makes the electronic circuit simple and improves the temperature stability.

Key words: amorphous silicon (a-Si), X-ray, sensor, heterojunction

1. Introduction

Semiconductor radiation (X-ray, gamma-ray, etc.) sensors are widely used in various medical, scientific and industrial systems. The semiconductor sensor has a lot of advantages over other kinds of radiation detector: larger signal current than ionization chambers, a possibility of small dimensions, no need of applied voltage, a good sensitivity and high speed of response [1-6]. High purity silicon is the most useful semiconductor material for the fabrication of semiconductor radiation sensors, mainly due to the ease in obtaining a thick depletion layer, the large carrier mobility and long lifetime for minority carriers [4-7].

For a semiconductor X-ray sensor, in order to obtain a charge signal in the external circuit associated with the sensor, holes and electrons excited by X-ray must be collected at the sensor electrodes. To accomplish this, an electric field must be present over the entire sensitive region of the sensor, and the strength of the field must be adequate to produce fast collection before carrier recombination or trapping

occurs. The most common method of achieving the required electric field in the volume of a sensor is to employ p-n or p-i-n junction structure biased in the reverse direction (or zero bias). In the former case, the depletion layer reaches only part way through the material and the sensitive detection volume is limited to the depletion layer. In the p-i-n diode structure, the "intrinsic" or high resistivity-bulk is totally depleted and thin p and n opposing faces provide non-injecting contacts.

Usually, the p-n or p-i-n junctions are formed by the high-temperature diffusion of impurities, such as boron and phosphorus. However, the high diffusion temperature (about 1000°C) process makes the carrier lifetime shorten, and thereby decreases the carrier collection efficiency and the sensor sensitivity. If the low-temperature deposition technology of amorphous silicon is applied to form a p-n or p-i-n structure, the carrier lifetime will not be shortened, and therefore high sensitivity can be obtained.

In this paper, with a full utilization of the advantage of low-temperature process of a-Si and the

advantage of long carrier lifetime of high-purity crystalline silicon, we have developed a new type of a-Si/c-Si double heterojunction sensor. The sensor structure is Au/p a-SiC/n NTD c-Si/n a-Si/Al. High-purity NTD (neutron transmutation doping) crystalline silicon (c-Si) was used as substrate. Major peculiarities of this kind of X-ray sensor are enumerated below:

1) The high purity NTD c-Si has a long carrier lifetime (about 400 μ s), and the low deposition temperature of a-Si makes no adverse effects on the carrier lifetime. Therefore, large photogenerated carrier collection efficiency and high sensitivity can be obtained.

2) The carrier confinement effect at the heterojunction of a-SiC and c-Si also largely improves the sensor sensitivity.

3) This kind of X-ray sensor can be used under zero-bias condition. The zero-bias operation makes the electronic circuit simple and improves the temperature stability.

2. Sensor Structure and Detection Mechanism

As a simplest analogy, a semiconductor X-ray sensor can be described as an ionization chamber in which the gas has been replaced with a solid semiconductor. Figure 1 shows a schematic diagram of the a-Si/c-Si double heterojunction X-ray sensor. The sensor consists of two conducting electrodes and a p-i-n diode structure. When X-ray (or gamma ray, and other charged particle) is incident upon a semiconductor, electron-hole pairs are generated by the excitation of electrons from the valence band to the conduction band due to the photoelectric effect,

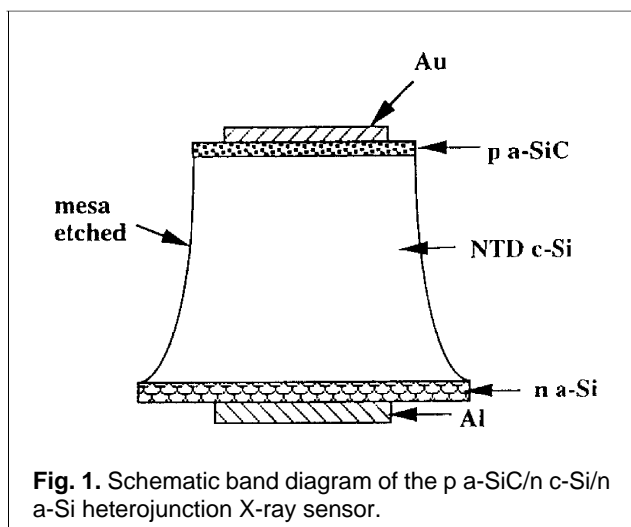


Fig. 1. Schematic band diagram of the p a-SiC/n c-Si/n a-Si heterojunction X-ray sensor.

Compton effect and collisions between the atoms and the secondly electrons (Auger electrons, photoelectrons etc.). The electrons and holes can be collected at the respective electrodes as a drift current in the built-in electric field region or as a diffusion current in the neutral region. As a result, a current proportional to the X-ray dose-rate absorbed flows through the sensor.

If a reverse bias voltage is applied across the electrodes, the strength of electric field in the sensitive volume of sensor will be enhanced and the carrier collection efficiency will be increased due to the decrease in the carrier loss factor from the recombination and trapping. Then the signal current will also be increased.

The signal current density J can be expressed in the form:

$$J = \int \Phi_0(\lambda) [1 - \exp(-\alpha_m(\lambda) \cdot \rho \cdot t)] \cdot \frac{hc}{\lambda} \cdot \frac{1}{\epsilon} \cdot q \cdot \eta_c(F \cdot \mu \cdot \tau) \cdot d\lambda \quad (1)$$

where $\Phi_0(\lambda)$ denotes the photon flux density, $\eta_c(F \cdot \mu \cdot \tau)$ is the collection efficiency, and other quantities are explained as follows:

λ = X-ray wavelength

q = elemental charge

$\alpha_m(\lambda)$ = mass absorption coefficient

ρ = density of semiconductor Si

t = thickness of semiconductor Si

hc/λ = photon energy

ϵ = average energy required to produce an electron-hole pair, and equal to 3.6eV for c-Si

F = strength of electric field

μ = carrier mobility

τ = carrier lifetime

h = Planck's constant

c = velocity of light

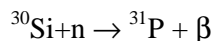
According to the Jacob's empirical formula [5], the number N_0 of electron-hole pairs created in 1 cm^3 of silicon per second can be approximately expressed by

$$N_0 = 5.8 \times 10^8 \times I \quad (2)$$

where I is the X-ray intensity expressed in mR/min.

3. Fabrication Process

The device was made on a NTD c-Si substrate with a thickness of about 0.5 mm. The NTD single crystal silicon used in this work was prepared from high purity FZ (float zone refining) silicon single crystal by the neutron transmutation doping method due to the following nuclear reaction [6]:



where ^{30}Si is the isotope of ^{28}Si , and constitutes about 4% natural silicon. When silicon crystal is irradiated by neutron beam, a part of ^{30}Si is converted to ^{31}P , and the resulting phosphorus acts as a donor in the silicon crystal. This doping method has been widely employed to achieve very homogeneous doping of high-quality crystal silicon. The resistivity of the NTD c-Si used in this work is about 250 ohm-cm and the minority carrier lifetime is about 400 μ s. By the low-temperature photoluminescence measurement, there are no impurities with the concentration above 10^{13} cm $^{-3}$ [8].

The (111) NTD c-Si substrate wafers were mirror polished on both sides. They were dipped in light HF solution and then loaded into the plasma CVD chamber. The p type a-SiC and n type a-Si layers were deposited respectively on the front and back surface of the substrate by the RF glow discharge deposition technique from SiH $_4$ /H $_2$ (1/9) mixture containing a desired amount of CH $_4$, B $_3$ H $_6$ and PH $_3$. The substrate temperature during the deposition is 180°C, the gas pressure is 1.0 Torr and the total gas flow rate is about 100 sccm. The thicknesses of p a-SiC and n a-Si layer are 300 and 500 Å, respectively. The p a-SiC and n a-Si layers were doped with B $_2$ H $_6$ and PH $_3$ at the gaseous ratios 0.2 vol.% and 1.0 vol.%, respectively. The optical gap of p a-SiC layer is about 1.9eV. Evaporated Au and Al films were used for the front and back electrodes. The area of the device is about 20 mm 2 .

4. Sensor Characteristics and Discussion

Firstly, the diode characteristics of these devices have been examined at room temperature. Figure 2 shows a typical current-voltage curve of the device. As can be seen, the diode characteristic is quite good, and the rectification ratio reaches 10^9 for the reverse bias voltage of 5 volts.

Secondly, the X-ray detection sensitivity of these sensors was measured with an X-ray diffractometer fitted with a copper target X-ray tube and a standard

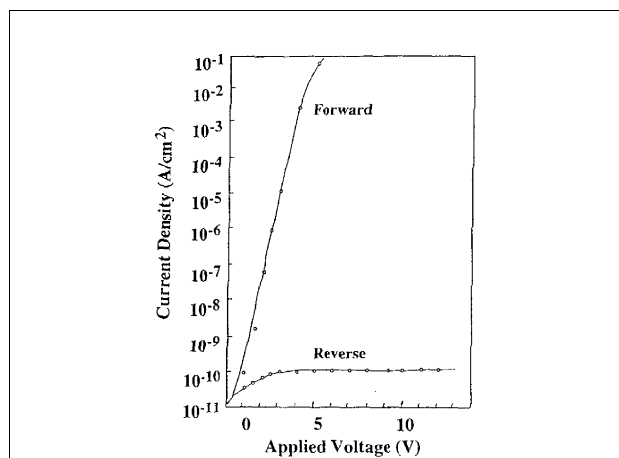


Fig. 2. Current-voltage characteristic of the p a-SiC/n c-Si/n a-Si diode

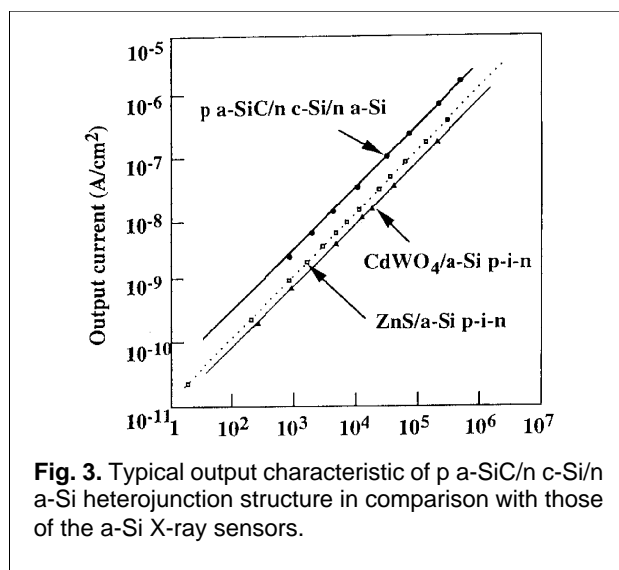


Fig. 3. Typical output characteristic of p a-SiC/n c-Si/n a-Si heterojunction structure in comparison with those of the a-Si X-ray sensors.

X-ray sensor. The sample used for the measurement was put in a light-tight box in order to avoid visible-light illumination. The output signal current was measured by a sensitive galvanometer. Figure 3 shows an experimentally obtained relationship between X-ray intensity and the output current for such a device. For comparison, the output characteristics of a-Si X-ray sensors with the structure of ZnS/a-Si p-i-n and CdWO $_4$ a-Si p-i-n reported in the previous papers [2] are also shown in this figure. As can be seen, the sensitivity of the sensor with the structure of p a-SiC/n c-Si/n a-Si is larger than the others.

The applied bias voltage dependence of the X-ray detection sensitivity of this kind of sensor has been also measured. The result is shown in Fig. 4 (curve (a)). It is seen that the sensitivity increases with the reverse bias voltage at first and then tends to saturate.

Temperature effect on the device output current has been measured as a function of ambient temperature ranging from 20°C to 30°C. The result is also shown in Fig. 4 (line (b)). The temperature coefficient is found to be about 0.8%/°C.

The energy band diagram for the p a-SiC/n c-Si/n a-Si heterojunction structure can be suggested as shown in Fig. 5. As can be seen, there is a high blocking barrier for electrons at the p a-SiC/n c-Si interface and also a high blocking barrier for holes at the n c-Si/n a-Si interface. Therefore, the back diffusion of electrons from c-Si into p a-SiC layer and that of holes from c-Si into n a-Si layer might be practically blocked. Due to this carrier confinement effect, the collection efficiency of the carriers generated by the incident X-ray might be improved and the sensitivity of the sensor might be increased.

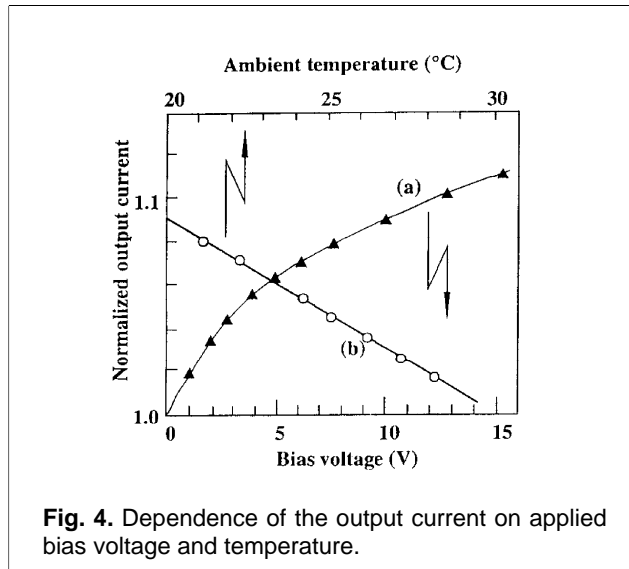


Fig. 4. Dependence of the output current on applied bias voltage and temperature.

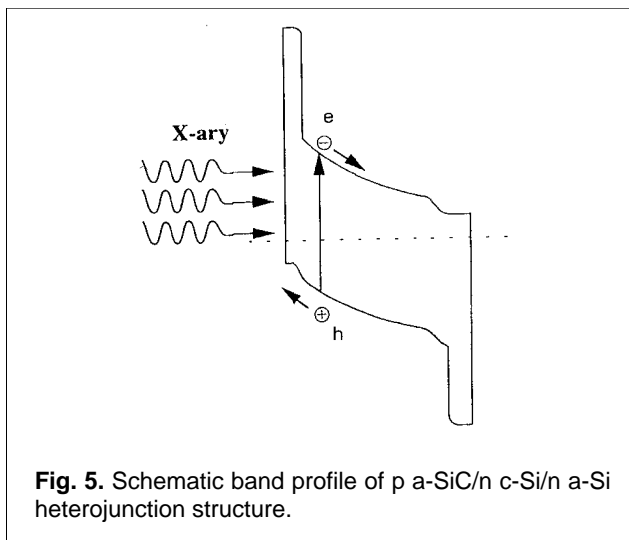


Fig. 5. Schematic band profile of p a-SiC/n c-Si/n a-Si heterojunction structure.

Hence, the X-ray detection sensitivity of these sensors is larger than that of the gold surface barrier type X-ray sensor.

The NTD c-Si used in this work has a long minority carrier (hole) lifetime, and the low deposition temperature of a-Si does not make the hole lifetime short. Since the hole diffusion coefficient D_p is about 13 cm²/sec, then the hole diffusion length $L_p=(D_p t_p)^{1/2}$ is estimated to be about 0.72mm. So it is suitable to choose the thickness range of the substrate wafer between 0.5-1 mm for the zero-biasing operational mode.

According to Eq. (2), if all of these electron-hole pairs generated by X-ray are collected at the electrodes, the output current density J can be given by

$$J = N_0 V q / S \quad (3)$$

$$= N_0 t q \quad (3)$$

where q is the elemental charge, and V , S , t are the volume, surface area, thickness of the device, respectively. For our samples having a thickness of 0.5 mm, the measured output current density J agrees with the calculated result from Eq. (3). For example, if the X-ray intensity is 500 mR/min, the signal current density J is equal to 4.7×10^{-9} A/cm² from Eq. (3), which agrees well with the experimental result shown in Fig. 3.

5. Conclusion

A new kind of a-Si/c-Si double heterojunction X-ray sensor with the structure of Au/p a-SiC/n c-Si/Al a-Si/Al has been developed. The characteristics of this kind of X-ray sensor have been examined. The linear relationship between output current and X-ray intensity is good, and the sensitivity is high. The peculiarities of this kind of X-ray sensor are summarized as follows:

1) The high-purity NTD c-Si has a long carrier lifetime (about 400 μs), and the low deposition temperature of a-Si makes no adverse effects on the carrier lifetime. Therefore, large photogenerated carrier collection efficiency and high sensitivity can be obtained.

2) The carrier confinement effect at the heterojunction of a-SiC and c-Si also largely improves the sensor sensitivity.

3) This kind of X-ray sensor can be used under zero-bias condition. The zero-bias operation makes the electronic circuit simple and improves the thermal stability.

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