Abstract—The hydrogenated amorphous silicon-germanium (a-Si$_{1-x}$Ge$_x$:H) pin x-ray detector has been fabricated successfully. It is found by introducing germanium into the amorphous silicon film, the detection efficiency of the x-ray is almost twice improved. This is due to the fact that the energy gap of the a-Si$_{1-x}$Ge$_x$:H material is smaller than that of the a-Si:H material.

Index Terms—a-SiGe:H, pin, x-ray detector.

I. INTRODUCTION

The hydrogenated amorphous silicon (a-Si:H) has received extensive interest recently. It is appealing not only for its low cost, easy fabrication processes, and potential use in many electronic solid-state theory based on periodic arrangement of atoms [1]–[7]. Spear and LeComber [2] first showed that by incorporating diborane (B$_2$H$_6$) or phosphine (PH$_3$) as the dopant gas, glow discharge amorphous silicon can be doped either p or n type, which makes it useful for device applications. To date, there have been many useful applications based on a-Si:H such as low cost solar cells [3], thin film transistors [4], visible light emitting diodes [5], color detectors [6], and edge and orientation detectors [7] for neural network image processing.

Since by alloying with other materials the optical and electronic properties of the material could be tailored, the studies of hydrogenated amorphous binary alloys have been intensive [5], [6], [8]. For examples, alloying a-Si:H with carbon will result in a-SiC:H, whose optical gap will be higher. Thus it will be suitable for the shorter wavelength applications such as visible light emitting diodes or color detectors [5], [6]. By alloying a-Si:H with germanium will result in the decrease of the optical gap, which will be suitable for longer wavelength applications such as solar cells or photo-detectors [8]. By integrating materials with different optical gaps as the i layer, the spectral response of the pin diode can be adjusted, thus make it more efficient for terrestrial solar cell applications or multiple color detectors. Since the hydrogenated amorphous silicon germanium alloys (a-SiGe:H) have smaller optical gap, it is also suitable for the fabrication of solar cells in tandem structure, which not only tailors the spectral response but also alleviates the Staebler-Wronski effect [9], i.e., light induced degradation in electrical and optical properties.

CsI and PbWO$_4$ are traditionally used as x-ray or γ-ray conversion layer of a photodetector [10]–[14]. The luminescence peak of CsI(Tl) and PbWO$_4$ are 560 nm and 510 nm, respectively [15]–[17]. Although the peak of the spectral response of a-Si:H pin photodetector is around 570 nm [21]–[24], matches the luminescence peak of CsI(Tl) and PbWO$_4$ better than a-SiGe:H’s, a-SiGe:H is used because of its small energy gap and therefore large photon-induced current. The hydrogenated amorphous silicon germanium pin x-ray detector may achieve a better efficiency to x-ray by modulating the germanium to silicon ratio. In this paper, we present the evidence that this is indeed the case.

II. EXPERIMENTAL

First, 100 nm thick Cr was e-beam evaporated on 7059 glass. Then 5–10 nm thick (p) a-Si:H layer doped with 500–1500 ppm B$_2$H$_6$ [25], [26] was deposited on Cr by plasma-enhanced chemical vapor deposition (PECVD), followed by the 200 to 480 nm thick undoped a-Si:H or a-Si$_{1-x}$Ge$_x$:H layers with $X_g = 0.2$, where $X_g$ is the ratio of GeH$_4$ gas flow rate to the total SiH$_4$ + GeH$_4$ flow rate, finally a 10–15 nm thick n+a-Si:H layer doped with 500–2000 ppm PH$_3$ [25], [26] was deposited. The substrate temperature, RF power density and chamber pressure during deposition were 200 °C, 0.11 W/cm$^2$, 0.4 torr, respectively. The true Ge composition in the solid film deposited in conditions above for $X_g = 0.2$ is 0.56 [27], which our previous studies has reported. The gas flow rates for p-layer deposition were 0.8 (H$_2$), 5 (SiH$_4$) and 1.2 (diluted B$_2$H$_6$) sccm, for undoped a-Si:H layer were 2 (H$_2$) and 5 (SiH$_4$) sccm, for undoped a-Si$_{0.44}$Ge$_{0.56}$:H layer ($X_g = 0.2$) were 2 (H$_2$), 4 (SiH$_4$) and 1 (GeH$_4$) sccm, for n$^+$-layer deposition were 0.8 (H$_2$), 5 (SiH$_4$) and 1.2 (diluted PH$_3$) sccm, respectively. The PH$_3$ and B$_2$H$_6$ gas were diluted with H$_2$ (PH$_3$H$_2$ = 3 : 7, B$_2$H$_6$H$_2$ = 3 : 5) to modulate the doping concentration. Under the above doping conditions, the dark conductivities of the n$^+$ and p$^+$ a-Si:H layers are $2.5 \times 10^{-3}$ and $6.2 \times 10^{-5}$ (Ω-cm)$^{-1}$ [28], respectively. The samples were then loaded into sputtering chamber immediately after taken out from PECVD chamber. The 200 nm thick ITO (Indium Tin Oxide) was sputtered on n$^+$ a-Si:H layer, it was patterned and wet etched. Then photoresist was spun on and the contact region of the pin cell was defined and opened, followed by the thermal evaporation of 10 nm thick Cr and 550 nm thick Au. Finally the Au and Cr were lifted off and then the a-Si:H/a-Si$_{0.44}$Ge$_{0.56}$:H pin cell was wire bonded with gold wire. The device structure is shown in Fig. 1.

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Fig. 1. Schematic device structure of the a-Si$_{1-x}$Ge$_x$:H pin detector.

The spectral response of the a-Si:H/a-Si$_{0.44}$Ge$_{0.56}$:H pin cells is measured using ARC Spectra-Pro 275 monochromator. The generated photo current is detected by the DSP lock-in-amplifier (Stanford Research System Model SR830). The x-ray source is the Cu K$_\alpha$ line (1.540 56 Å). The CsI(Tl) or PbWO$_4$ material which was deposited on the glass substrate absorbs x-ray and converts it to visible light. An a-Si:H or a-Si$_{0.44}$Ge$_{0.56}$:H pin cell is placed about 10 cm away from the glass substrate. The visible light propagates to the PIN photo-detector and is absorbed. The generated photocurrent is amplified by the low noise current pre-amplifier (Stanford Research System Model SR570) and transforms into a voltage signal. The KEITHLEY 617 Electron Meter reads the voltage signal. All the system is placed in a Pb-glass-box. Before the experiment, the pin photodetector was exposed directly to the x-ray and there was no response signal at all.

III. RESULTS AND DISCUSSION

Fig. 2 shows the $I$–$V$ characteristics and device structure of the sample RX09 a-Si:H pin detector which was measured under the microscope without (white light) or with red, green or blue filter. The red, green and blue filters are those whose transmission coefficients are above 90% in the wavelength range of longer than 600 nm, 500–600 nm, and shorter than 550 nm, respectively. The n, i, and p layer is 10, 350, and 10 nm in thickness, respectively. The doping concentration of n and p layer is 1500 ppm PH$_3$ and 2000 ppm B$_2$H$_6$, respectively. It is observed that by subtracting the dark current from the red light $I$–$V$ curve, the photo response increases slightly as the reverse bias increases, it indicates that the collection width of a-Si:H pin detector at zero bias is slightly smaller than the i-layer thickness (350 nm), so the carriers photogenerated deep in the back of the cell by red light, i.e., near i-p interface, could not be completely collected.

Fig. 3 shows the $I$–$V$ characteristics of the sample RY03 a-Si$_{0.44}$Ge$_{0.56}$:H pin detector under the illumination of a lamp through a microscope without (white light) or with red, green or blue filter. The area of pin detector is $5 \times 10^{-2}$ cm$^2$.

Fig. 4(a) and (b) show the $I$–$V$ characteristics and device structure of the sample RY05 a-Si$_{0.44}$Ge$_{0.56}$:H pin cell, respectively. The n, i, i and p layer is 10, 10, 200, and 10 nm in thickness, respectively. The first i-layer is a-Si:H whereas the second i-layer is a-Si$_{0.44}$Ge$_{0.56}$:H with $X_g = 0.2$. The doping concentration of n and p layer is 1500 ppm PH$_3$ and 2000 ppm B$_2$H$_6$, respectively. The undoped 10 nm a-Si:H layer is designed as a stop layer to prevent PH$_3$ from n-layer during plasma deposition so the n-p interface has been pushed downward from original n-i interface. We need a “protecting layer” to protect a-Si$_{0.44}$Ge$_{0.56}$:H layer against PH$_3$. The intrinsic a-Si:H layer of RY05 is designed to achieve this goal.

Fig. 4(a) and (b) show the $I$–$V$ characteristics and device structure of the sample RY05 a-Si$_{0.44}$Ge$_{0.56}$:H ($X_g = 0.2$) pin cell, respectively. The n, i, i and p layer is 10, 10, 200, and 10 nm in thickness, respectively. The first i-layer is a-Si:H whereas the second i-layer is a-Si$_{0.44}$Ge$_{0.56}$:H with $X_g = 0.2$. The doping concentration of n and p layer is 1500 ppm PH$_3$ and 2000 ppm B$_2$H$_6$, respectively. The undoped 10 nm a-Si:H layer is designed as a stop layer to prevent PH$_3$ in n layer from entering into the underlying i a-Si$_{0.44}$Ge$_{0.56}$:H layer during the deposition of n-i-layer by PECVD. Subtracting the dark curve from the red, green or blue $I$–$V$ curves, there is almost no increase between curves in the reverse bias region when magnitude of the bias is larger than 1.5 V. This indicates that the collection width of pin junction has moved back to top n-i interface by including an additional undoped a-Si:H layer and reached the depletions.
edge of the n-p junction. But this structure causes apparently
the crossover between the light and the dark curves in the for-
ward bias region. This indicates that the depletion layer of
the n-p junction does not extend to the edge of the i-layer, a neutral
i-layer with high series resistance exists.

Fig. 5(a) and (b) show the spectral response of the sample
RX09 a-Si:H and RY05 a-SiGe:H pin cell, respectively.
The peak response of RX09 a-Si:H detector is at 570 nm as
shown in Fig. 5(a). The peak response of the sample RY05
a-SiGe:H pin detector, shown in Fig. 5(b), shifts toward
longer wavelength at 590 nm as expected.

Fig. 6 shows the response of a-Si:H/a-SiGe:H pin
x-ray detector with CsI or PbWO$_4$ conversion layer. The current
is recorded as the difference between photo (x-ray on) and dark
(x-ray off) current. The thickness of CsI and PbWO$_4$ are 200
nm and 5 $\mu$m, respectively. Since the optical gap of the sample
RY05 a-SiGe:H pin detector shifts to lower energy as
compared to that of the sample RX09 a-Si:H pin detector, the
magnitude of response current of a-SiGe:H pin x-ray detector
is almost twice as the a-Si:H pin x-ray detector with
either the CsI(Tl) or PbWO$_4$ conversion layer. The thickness of
the conversion layer does not affect the magnitude of response
current. It is because that although the CsI(Tl) is 5 $\mu$m thick,
the CsI(Tl) film is opaque to visible light and the luminous
photons from the region of film closed to x-ray source can not
go through opaque CsI film nor reach the detector.

IV. C ONCLUSION

The a-Si:H pin cell with a-Si:H ($X_g = 0$) i-layer can
achieve a collection width slightly less than 350 nm. The
niip a-Si$_{0.44}$Ge$_{0.56}$:H pin cell using 10 nm undoped a-Si:H
layer to stop PH$_3$ percolating into the underlying undoped
a-Si$_{0.44}$Ge$_{0.56}$:H ($X_g = 0.2$) layer can only achieve a collec-
tion width around 200 nm.

The magnitude of x-ray response of a-Si$_{0.44}$Ge$_{0.56}$:H pin x-ray
detector, however, is almost twice of the a-Si:H pin x-ray detector
with either CsI(Tl) or PbWO$_4$ conversion layer. The reason is that the optical gap of a-Si$_{1-x}$Ge$_x$:H is smaller than that of a-Si:H although the spectral response of a-Si:H pin cell is more matching to the luminescence spectra of CsI(Tl) or PbWO$_4$.

REFERENCES


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