비정질 실리콘 방사선 계측기에서의 Photoconductive Gain의 응용

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Utilization of Photoconductive Gain Mechanism in Amorphous Silicon Radiation Detectors

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ABSTRACT

The photoconductive gain mechanism in various types of hydrogenated amorphous silicon devices, such as p-i-n, n-i-n and n-i-p-i-n structures was investigated in connection with applications to radiation detection. We measured the photoconductive gain in two time scales: one for short pulses of visible light (< 1 μsec) which simulate the transit of energetic charged particles, and the other for rather long pulses of light (~1msec) which simulate x-ray exposure in medical imaging. We used two definitions of photoconductive gain: current gain and charge gain which is an integration of the current gain. We found typical charge gains of 3 ~ 9 for short pulses and a few hundred for long pulses at a dark current density level of 10 mA/cm^2.

INTRODUCTION

Hydrogenated amorphous silicon (a-Si:H) p-i-n photodiodes have been successfully investigated for applications to detection of visible light, x-rays, γ-rays, charged particles and neutrons.[1-3] The usual way of detecting radiation using a-Si:H p-i-n diode is to apply a reverse bias on the diode and measure the signal which is induced by the motion of the photo-generated charge carriers along the depletion field in the i-region. The maximum number of charge carriers collected in a reverse biased p-i-n diode is equal to the number of photo-generated charge carriers, i. e., is equal to the number of photons which had interactions in the i-region of the diode, hence the maximum gain, which is defined as the ratio of the collected charge to the number of interacted photons, is unity.

The photoconductive gain mechanism in a-Si:H, which is primarily due to hole trapping and subsequent charge neutralization, has been investigated with various structures such as metal-i-metal, n-i-n, p-i-n (under forward bias) and n-i-p-i-n, and photoconductive gains of more than a hundred for the steady state photocurrent were reported.[4] Optical imaging devices utilizing this gain mechanism, which were based on Schottky diodes or n-i-n photoconductors with coplanar or sandwich structures, have been successfully made from a-Si:H.[5-7]

For the radiation detection using a-Si:H, CsI(Tl) is usually coupled to a-Si:H devices to convert the radiation to visible light, and the fluorescence decay time of CsI(Tl) is about 1 msec. Hence, the duration of light exposure from CsI(Tl) is about 1 msec for fast transit charged particles or γ-rays, and a few milliseconds for x-ray exposures in radiography. For ordinary a-Si:H, it takes hundreds of microseconds or even a few milliseconds to achieve steady state photoconductive gain. Therefore, during the short period of light exposure from CsI(Tl) in radiation

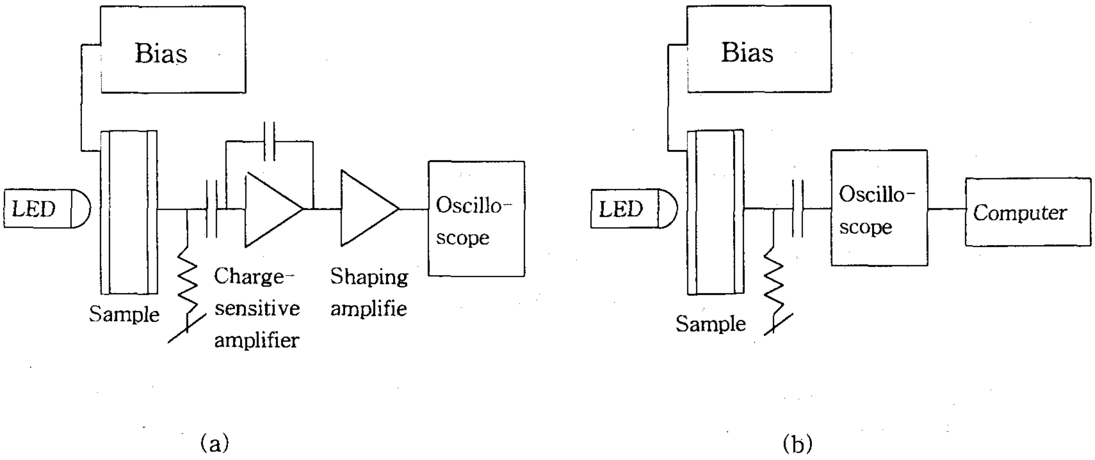


Fig. 1 Experimental system for photoconductive gain measurement. (a) For the short LED pulse the conventional radiation measurement system was used, and (b) with a long LED pulse the photocurrent was directly read by the oscilloscope via ac coupling.

detection, the full photoconductive gain may not be achieved with a-Si:H devices. If, however, a moderate gain can be obtained during a rather short period, this photoconductive gain mechanism may be applied to radiation detection such as a single charged particle or γ-ray detection and medical x-ray imaging.

In this paper the experimental results of the gain with a-Si:H p-i-n, n-i-n and n-i-p-i-n devices for rather short period of light pulses are discussed.

EXPERIMENTAL

Test samples were fabricated using a PECVD machine and all of the samples had sandwich structure. The thickness of the i-layer were 1 ~ 30 μm for p-i-n diodes, 1 μm for the thick i-layer of n-i-p-i-n diodes and 14 μm for n-i-n samples. The thin i-layer in the n-i-p-i-n diodes was about 30 nm thick, and the p-layer was about 15 nm thick and slightly doped (500 ppm of diborane) to suppress the dark current without affecting the photoconductive gain mechanism by recombination of electrons in the p-layer[5]. The n- and p-layers of the p-i-n diodes were thick enough to prevent tunneling of electrons and holes in reverse biased condition, but thin enough to let the visible light pass through. These layers provided ohmic contacts in forward bias which is essential for the photoconductive gain.

The measurements of photo-signals were performed in two different time scales. In order to simulate the transit of fast charged particles, an LED light pulse of 0.2 μsec pulsewidth was use, and for the simulation of x-ray exposure, 1 ~ 30 msec of LED light was incident on the samples. The conventional experimental system for detecting a single particle was used for the short pulse measurement, and is shown in Fig. 1 (a). The gain of a p-i-n or n-i-n diode was calculated by dividing the photo-signal in forward bias by the maximum signal in reverse bias, which was also used to calculate the gain in n-i-n device which had the same thickness and transparency as the corresponding p-i-n diode. For the long pulse measurement, the photocurrents from the sample devices were directly measured as shown in Fig. 1 (b). Using ac coupling, the dc dark current could be separated from the photocurrent. the RC time constant of the system was made long enough to prevent decay of the photocurrent level. The measured photocurrent was integrated using a computer which is connected to the digital oscilloscope, and both current gain and charge gain were calculated by comparing the amplitude in forward bias and in reverse bias as in the short pulse measurements.

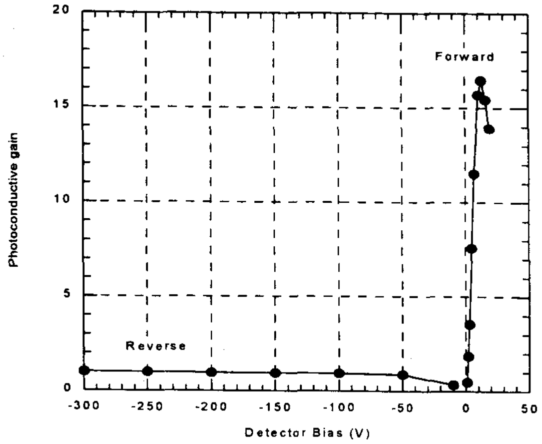
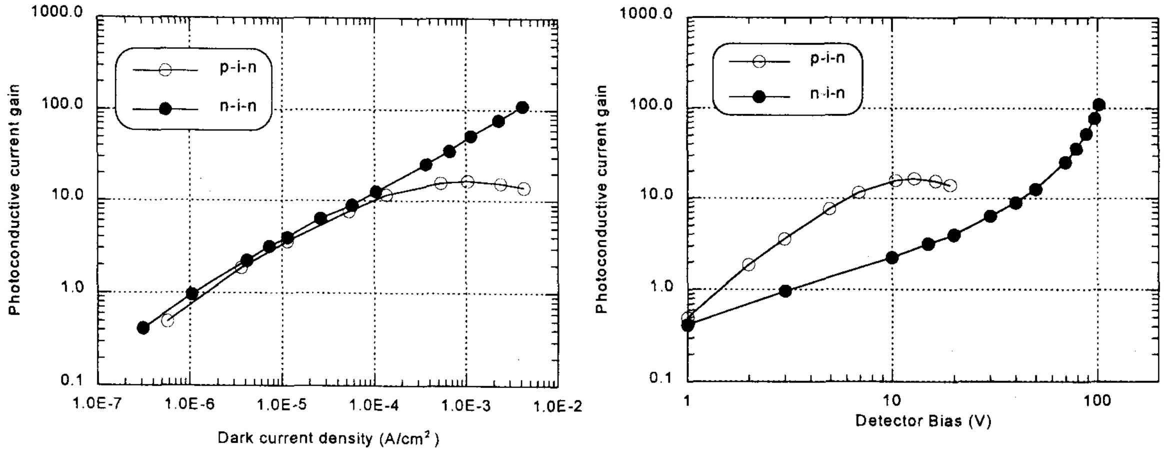


Fig. 2 The maximum photocurrent in a 14 μm thick p-i-n diode as a function of detector bias when 1 msec of light is incident.

RESULTS

For a 1 msec light pulse, the photocurrent obtained with a 14 μm thick p-i-n diode is shown in Fig. 2. The photocurrent is normalized to the maximum value in reverse bias to show the gain. To achieve a unity gain in reverse bias, the detector bias should be higher than the depletion bias which is defined as the required reverse bias for full depletion of the i-region. More than 200 V was needed to obtain the unity gain in reverse bias with this diode, while the unity gain could be achieved with about 1.5 V in forward bias. The photocurrent increased almost linearly with the applied forward bias and reached its maximum value of 17 at 13 V; the gain decreased at higher forward bias.

For a 1 msec light pulse, the current gain of the n-i-n device is compared with those of the p-i-n diode (same thickness) in Fig. 3 (a) and (b) as functions of the detector bias and dark current density, respectively. At low biases the gain in p-i-n diode is higher than that of n-i-n, but at higher biases the gain of the p-i-n diode decreases while that of the n-i-n keeps increasing and at 100 V the gain is 110. While the gain behavior of the p-i-n and n-i-n devices are different when plotted as a function of bias as in Fig. 3 (a), they showed similar dependences on the dark current density at low dark current density levels as shown in Fig. 3 (b). The gain of the n-i-n device was found to be proportional to $J_d^{0.6}$, where J_d is the dark current density. From these results, the photoconductive gain is mainly determined by the dark current density rather than the applied bias, and at low dark current densities, the gains of the p-i-n and n-i-n device of the same thickness were the same for the same dark current densities. The n-i-p-i-n diodes showed similar gain behavior as the n-i-n devices, because it is basically an n-i-n device with a very slightly doped p-layer which is thin and located close to one end of the device, hence the overall properties are similar to the n-i-n device except that it has the polarity of operation bias.



(a)

(b)

Fig. 3 Comparisons of the current gain in p-i-n diode and n-i-n device. The thickness of the devices is 14 μm and both have the same transparency.

The gains of 14 µm thick p-i-n and n-i-n devices for short light pulses (0.2 µsec) are shown in Fig. 4 as functions of dark current density with two different shaping amplifier integration times. Due to the long decay time of the photocurrent, longer integration time produced larger gains. For short light pulses, the behavior of the p-i-n and n-i-n devices were almost identical to each other for the same dark current densities. A similar behavior was also found with the n-i-p-i-n diode. The maximum gains obtained with our best samples at a dark current density of 10 mA/cm^2 were 6 and 9 for integration times of 1 µsec and 5 µsec, respectively.

CONCLUSION

The transient photoconductive gain was measured with p-i-n, n-i-n and n-i-p-i-n devices. For short light pulses (< 1 µsec), the gain was almost the same for all devices. For longer pulses (1 msec), n-i-n and n-i-p-i-n devices showed higher gains than p-i-n. At a dark current density level of ~10 mA/cm^2, a gain of 9 could be obtained for short light pulses and gains of more than 200 could be achieved for long pulses. Single charged particle or γ-ray detection using photoconductive gain mechanism is expected to have higher noise level due to the higher dark current density compared to the conventional methods of radiation detection. This can be, however, minimized by making pixel area small. Work is continuing to obtain higher gains at lower dark current density levels for the short light pulses.

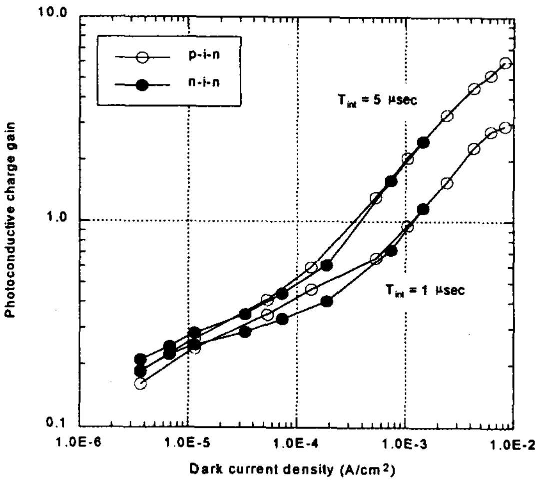


Fig. 4 The charge gains of p-i-n and n-i-n devices for 200 nsec of light pulses. The integration time was controlled in the shaping amplifier.

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