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비정질 실리콘을 이용한 방사선 계측시 Photoconductive Gain의 특성

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= Abstract =

Characteristics of Photoconductive Gain in Radiation Detection with a-Si:H Devices

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The photoconductive gain mechanism in amorphous silicon devices was investigated in connection with applications to radiation detection. Various device types such as p-i-n, n-i-n and n-i-p-i-n structures were fabricated and tested. Photoconductive gain was measured in two time scales : one for short pulses of visible light($<1\mu$sec) which simulate the transit of energetic charged particles or γ-rays, 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 obtained typical charge gains of 3~9 for short pulses and a few hundreds for long pulses at a dark current density level of 10mA/cm^2. Various gain results are discussed in terms of the device structure, applied bias and dark current density.

Key words : Photoconductive gain, Photocurrent, Photoconductivity, a-Si:H, p-i-n, n-i-n, n-i-p-i-n

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[1-5]. In most cases, amorphous silicon p-i-n photodiode is coupled to a scintillator layer which converts the incident radiation to visible light. These visible photons are then absorbed by the amorphous silicon p-i-n diode. The usual way of operating an amorphous silicon p-i-n diode to detect photons 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[6-8]. 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

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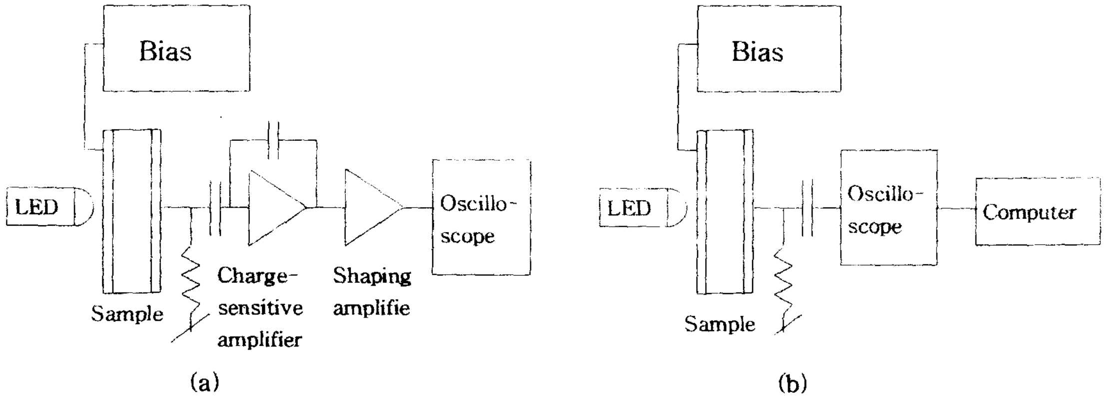


그림 1. Photoconductive gain 측정을 위한 실험장치의 개념도. (a) 짧은 LED 펄스에 대해서는 기존방식의 전형적인 방사선 계측 시스템을 사용하였고, (b) 긴 LED 펄스에 대해서는 광전류를 교류결합을 통하여 오실로스코프로 직접 획득하였다

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

successfully made from a-Si:H[9-11].

For 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 1μ sec[12]. Hence, the duration of light exposure from CsI(Tl) is about 1μ sec for fast transit charged particles or γ-rays, and a few milliseconds for x-ray exposure in radiography. For ordinary a-Si:H, it takes hundreds of microseconds or even a few milliseconds to obtain steady state photoconductive gain[7]. Therefore, during the short period of light exposure from CsI(Tl) in radiation 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, we describe the experimental results of the gain with a-Si:H p-i-n, n-i-n and n-i-p-i-n devices for short periods of light pulses, and discuss the behavior of the photocurrent in the transient state.

EXPERIMENTAL

Test samples were fabricated using a PECVD(Plasma Enhanced Chemical Vapor Deposition) machine, which is a kind of deposition machines used in semiconductor processing, and all of the samples had sandwich structure. The thickness of the i-layer were 1~30μm for p-i-n diodes, 1μm for the thick i-layer of n-i-p-i-n diodes and 14μm 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[7]. 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 0.2μsec pulse width was used, and for the simulation of x-ray exposure, 1~30μmsec 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 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

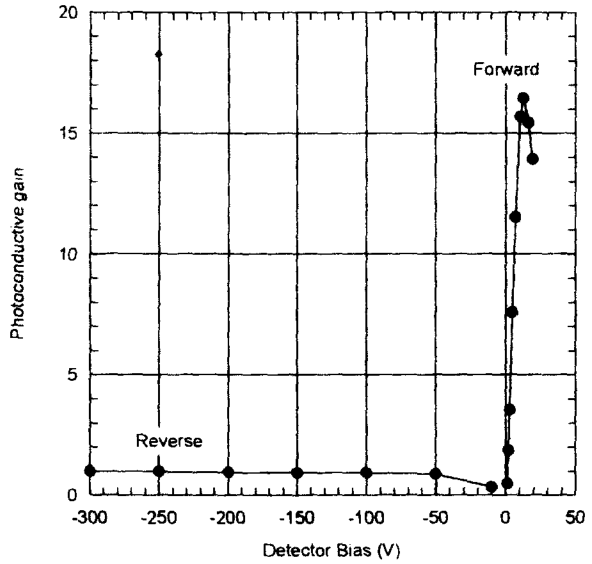


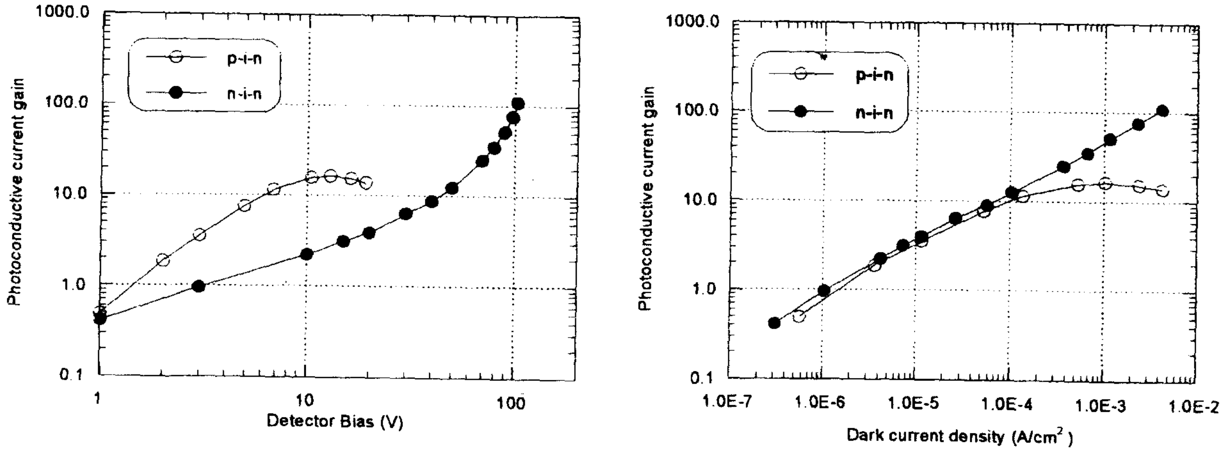
그림 2. 14μm 두께의 p-i-n 다이오우드에 1 msec의 빛을 비추었을 때 계측기 전압의 변화에 대한 최대 광전류의 변화
Fig. 2. The maximum photocurrent in a 14μm thick p-i-n diode as a function of detector bias when 1 msec of light is incident

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.

RESULTS

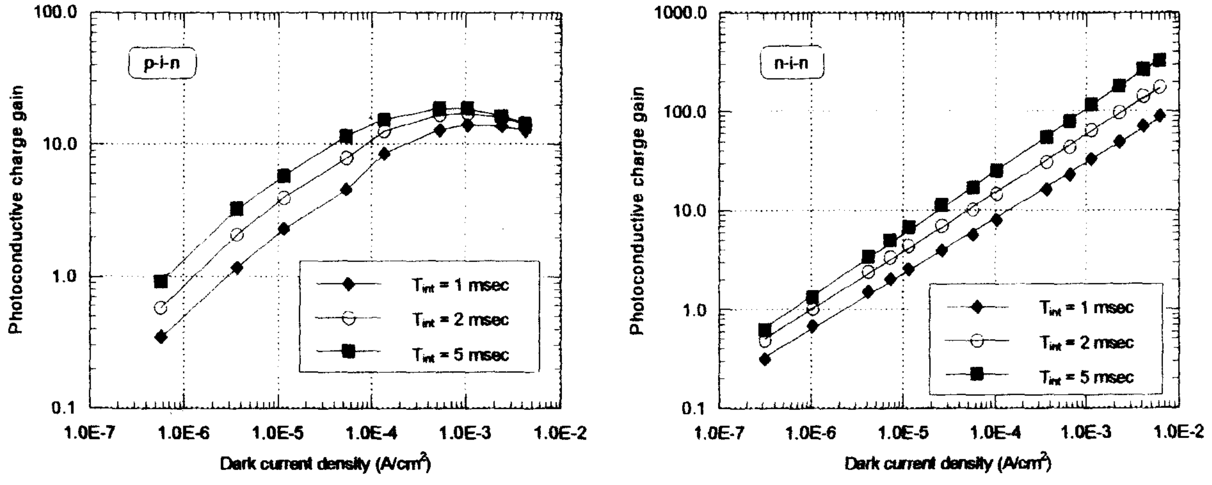
For a 1 msec light pulse, the photocurrent obtained with a 14μm thick p-i-n diode is shown in Fig. 2. The photocurrent is normalized to the maximum value in reverse bias to show the gain. To achieve a unity gain in reverse bias, the detector bias should be higher than the depletion bias which is defined 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 as discussed in the next section.

For a 1msec 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.



(a) (b)

그림 3. p-i-n과 n-i-n 소자의 전류 이득에 대한 비교. 소자들의 두께는 14 μm이고 다 같은 투명도를 가지고 있다
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



(a) (b)

그림 4. 14 μm 두께의 p-i-n 광다이오우드와 n-i-n 광전도체에서의 암전류밀도(dark current density)에 따른 Photoconductive 전하 이득의 변화. 1msec의 빛을 사용하였고, 전류 이득과 비슷한 양상을 보여주고 있다

Fig. 4. Photoconductive charge gains in 14 μm thick p-i-n photodiodes and n-i-n photoconductors as functions of dark current density. 1msec of light was exposed. Similar behaviors as in the current gains are seen

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 charge gains of a 14 μm thick p-i-n diode and a same thickness n-i-n photoconductor for 1msec light pulses are shown in Fig. 4 (a) and (b) as functions of dark current density with various integration times. Due to the long decay time of the photocurrent after shutting off the light, the charge gain is higher for a longer integration time in both p-i-n and n-i-n devices. The behaviors of the charge gain in p-i-n and n-i-n devices are very similar to those of the current gain described above. The maximum charge gain in the p-i-n diode for 5msec of integration time was about 20 at a dark current density of 0.5 μmA/cm², and for the same integration time a charge gain of 260 could be achieved with the n-i-n photoconductor at a dark current density of 6 μmA/cm². The charge gains in the n-i-n photoconductors were proportional to J_d^{α}, where $\alpha=0.56\sim0.63$.

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.

The gains of 14 μm thick p-i-n and n-i-n devices for short light pulses(0.2μsec) are shown in Fig. 5 as

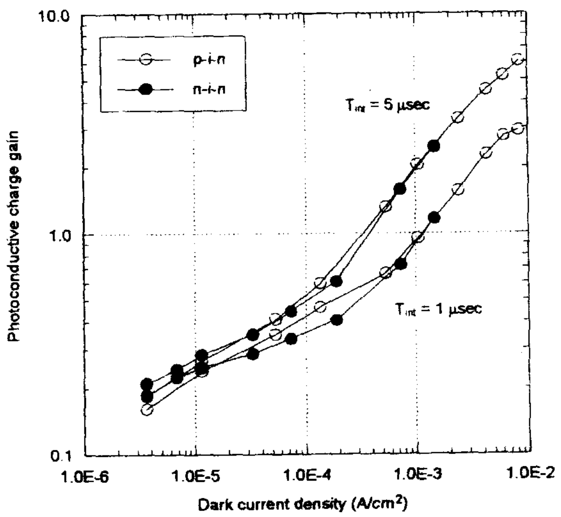


그림 5. 0.2μsec의 광펄스에 대한 p-i-n과 n-i-n 소자의 전하 이득. 적분시간은 shaping amplifier에서 조절하였다.

Fig. 5 The charge gains of p-i-n and n-i-n devices for 0.2μsec of light pulse. The integration time was controlled in the shaping amplifier.

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 higher 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 10mA/cm^2 were 6 and 9 for integration times of 1μsec and 5μsec, respectively.

DISCUSSION

For an insulator or a semiconductor with a single trap level, the transient photocurrent can be expressed as[13]

$$I_p(t) = qFdAG_p(1-e^{-t/\tau_r}) \quad \text{(rise)},$$
$$I_p(t) = qFdAG_p\, e^{-t/\tau_r} \quad \text{(decay)}, \qquad (1)$$

where, q is the electron charge, F is the generation rate of photon induced electrons per unit volume, d is the thickness of the device, A is the area, G_p is the steady state photoconductive gain defined as τ/t_r, τ is the lifetime of the majority carriers, t_r is the transit time of the majority carriers across the device and τ_r is the response time which is defined as $\tau n_t/n_f$, where n_f and n_t is the free and trapped majority carrier density, respectively. Since amorphous silicon has, however, a distribution of trap levels in the forbidden gap, a single exponential term cannot express the rise and decay shapes of the photocurrent, and multicomponent exponentials are needed to fit the shape of the time response[14]. For amorphous silicon photoconductor, the transient photocurrent can be written as

$$I_p(t) = I_{\max}(1-\sum_i a_i\, e^{-t/\tau_i}) \quad \text{(rise)},$$
$$I_p(t) = I_{\max} \sum_i a_i\, e^{-t/\tau_i} \quad \text{(decay)}, \qquad (2)$$

where, $I_{\max}$ is the photocurrent at steady state, τ_i is a response time which corresponds to the i-th trap and a_i is a weighting factor which represents the influence of the i-th trap to the photocurrent. The summation of a_i is equal to unity. In Fig. 6, the photocurrent shape with a 1 msec light pulse is shown with the curves fitted by Eq. (2), where a_i and τ_i were used as fitting parameters. In order to find the characteristics of the current decay, the photocurrents of p-i-n and n-i-n devices after a short pulse of light were measured and are compared in Fig. 7. At the same dark current density level, the initial decay times of the p-i-n and n-i-n devices are almost identical to each other, and this explains why their gains are almost the same for the short light pulses. At higher dark current density levels (Fig. 7 (b)), the photocurrent of the p-i-n diodes decays faster than that of the n-i-n devices in longer time scales. To extract more information about decay times in the long time scales, the time taken to reach 30% of the peak photocurrent after a 1 msec of light exposure, $T_{30\%}$, was measured with p-i-n and n-i-n devices and is shown in Fig. 8. The decay time of the n-i-n increases linearly with the detector bias while that of the p-i-n decreases as the bias increases and is approximately proportional to the reciprocal of the detector bias. The decreasing decay time constant may be explained by the decrease of the electron lifetime in the

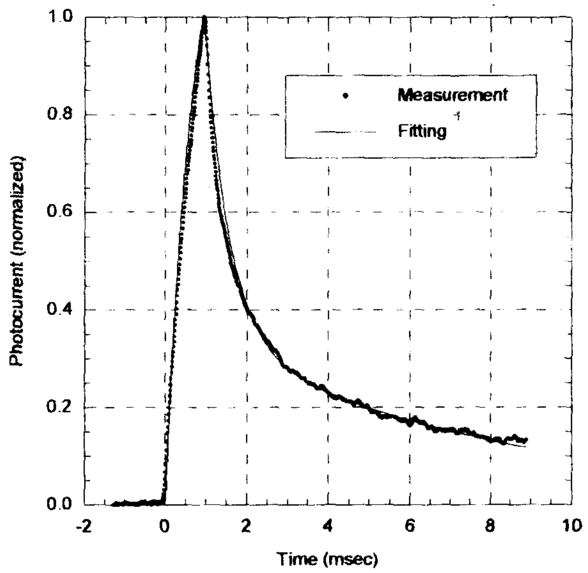
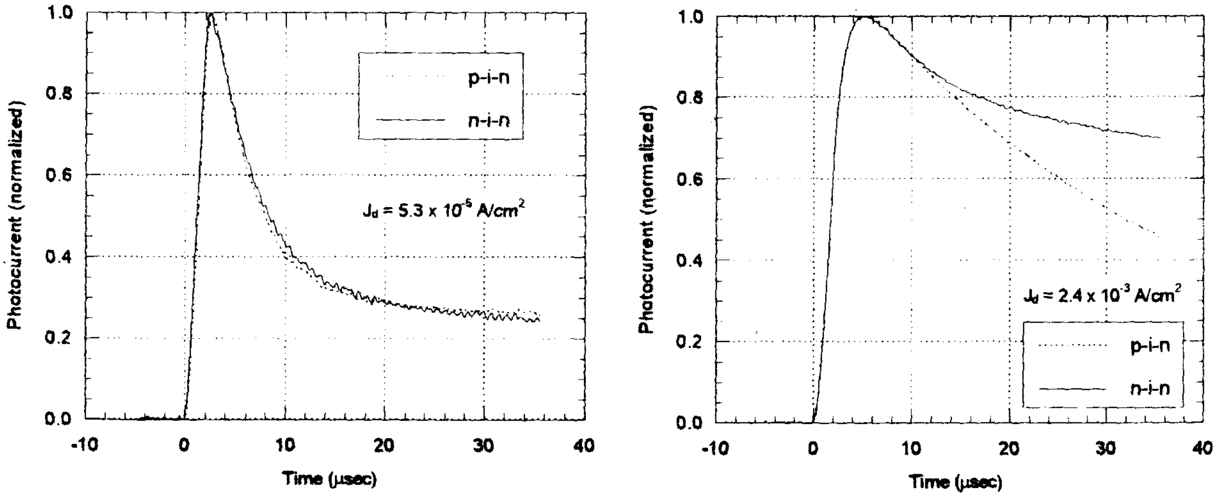


그림 6. 1 msec의 광펄스에 대한 p-i-n 다이오우드의 광전류 모양. 광전류는 최대치인 1 msec에서의 값으로 나누어 나타내었다. 3V의 forward bias를 부가하였고, (2)식을 사용하여 실험값들을 fitting하였다 .

Fig. 6. The photocurrent shape of a p-i-n diode with a 1 msec light pulse. The current is normalized to the maximum current at 1 msec. 3V of forward bias was applied. Eq. (2) was used to fit the measurements



(a)

(b)

그림 7. 짧은 광펄스를 비추었을 때 p-i-n과 n-i-n 소자들의 감소하는 광전류의 모양

Fig. 7. The decaying photocurrent shapes of p-i-n and n-i-n devices after a short light pulse

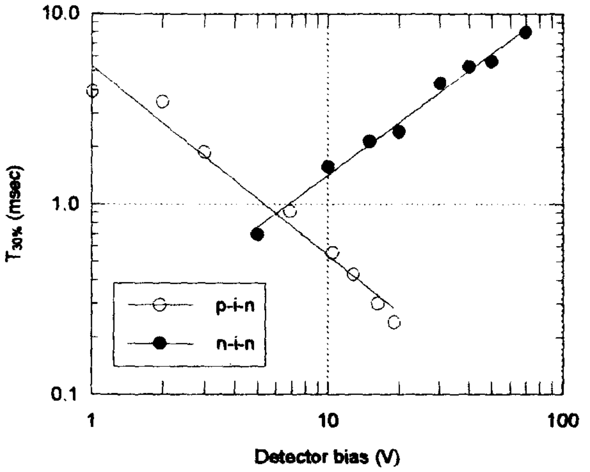


그림 8. p-i-n과 n-i-n 소자들의 $T_{30\%}$. $T_{30\%}$는 본문에 정의되어 있다

Fig. 8. $T_{30\%}$ of p-i-n and n-i-n devices. $T_{30\%}$ is defined in the text

p-i-n diode. As the forward bias increases, the dark current increases due to the increased number of electrons and holes by increased double injections from the contacts, and the quasi-Fermi levels of the electrons and holes move toward the band edges making the recombination centers broadened, hence more recombination of electrons and holes occurs and eventually the lifetime of the electrons decreases. Due to this decrease in the lifetime, the photocurrent of the p-i-n diode decreases at high biases, since I_{max} in Eq. (2) is proportional to the lifetime. At low biases, however, the decrease in the exponential terms with the bias is dominant, hence the photocurrent increases with the bias. The decrease of electron lifetime and photoconductive gain with the increased bias in p-i-n diodes has also been found by others[8].

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(< 1μsec), 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 ~10mA/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.

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=국문초록=

비정질 실리콘에서의 photoconductive gain mechanism을 방사선 계측시 이용하기 위한 연구를 수행하였다. p-i-n, n-i-n, n-i-p-i-n과 같은 여러 형태의 비정질 실리콘 계측기를 제작하고 시험하였다. Photoconductive gain은 두 가지의 시간적 범위에서 측정하였다 : 하나는 고에너지의 하전입자나 감마선의 통과를 모사하기 위해서 1μsec 보다 짧은 가시광선 펄스를 사용하였고, 다른 하나는 의학영상에 사용되는 x-선을 모사하기 위하여 보다 긴 1msec 정도의 가시광선 펄스를 사용하였다. 두 가지의 photoconductive gain-current gain과 charge gain-을 정의하여 실험하였으며, charge gain은 current gain을 시간에 따라 적분한 값이다. 10 mA/cm^{2}의 dark current density level에서, 짧은 펄스에 대해서는 3~9정도의 charge gain을 얻을 수 있었고 긴 펄스에 대해서는 수백의 charge gain을 얻을 수 있었다. 여러 가지의 gain에 대한 결과를 계측기의 구조, 부가전압, dark current density와의 관계를 통하여 논의하였다.