Amorphous Silicon/Silicon Carbide Superlattice Avalanche Photodiodes

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***Abstract*—A novel a-Si/SiC:H superlattice avalanche photodiode (SAPD) has been successfully fabricated on an ITO/glass substrate by plasma-enhanced chemical-vapor deposition (PECVD). The room-temperature electron and hole impact ionization rates, α and β, have been determined for the a-Si/SiC:H superlattice structure by the photocurrent multiplication measurements. The ratio α/β is 6.5 at a maximum electric field of 2.08×10^5 V/cm. Avalanche multiplication in the superlattice layer yields a high optical gain of 184 at a reverse bias $V_R = 20$ V and an incident light power $P_{in} = 5$ μW and has a switching time of 4.5 μs at a load resistance $R = 1.8$ kΩ.**

I. Introduction

In recent years there has been considerable interest in superlattice and multilayer avalanche photodiodes (SAPD's and APD's), originally proposed by Chin *et al.* [1], i.e., the graded-gap staircase APD [2], the multiquantum well APD [3], and the doped quantum well APD [4]–[6]. So far, all the APD's were made from crystalline material. In the present report, an a-Si/SiC:H superlattice APD with step-like multilayer barriers was formed. All of these structures are made of a heterostructure to spatially confine the carrier ionization events within the narrow-bandgap material. As the carriers move across the heterobarrier step, they gain kinetic energy from the bandgap discontinuity thus effectively reducing the impact ionization threshold energy. In this way each carrier will impact ionize a new electron–hole pair, and the ionization rate can be enhanced [7]. The characteristics of the multiplication are different from those of conventional band-to-band ionization.

The optical performance of an avalanche photodiode can be realized when the excess noise contribution from the avalanche process is minimized [8], [9]. For low-noise operation of an APD, the impact ionization rates for electrons and holes should be very dissimilar. As the conduction band-edge offset is substantially larger than the valence band-edge offset for an a-Si/SiC:H heterostructure, it is expected that α would be larger than β [10]. Therefore, a new a-Si/SiC:H SAPD is proposed. The advantages of an amorphous Si/SiC superlattice APD are: 1) a variety of peak response wavelengths is achievable by changing the composition and the well-to-barrier widths of the superlattice; 2) a large-area-detecter image sensor can be made on a glass substrate; and 3) the low-temperature process of the amorphous films (−230°C) possesses very abrupt composition change and a doping profile that are impossible in single-crystalline Si.

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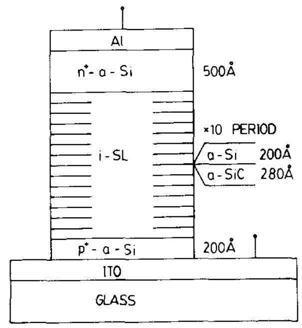

Fig. 1. The schematic cross section of the a-Si/SiC:H superlattice avalanche photodiode (SAPD).

II. Device Structure and Preparation

The schematic cross section of an a-Si/SiC:H SAPD is shown in Fig. 1. First, an indium tin oxide (ITO) coated Corning 7059 glass was used as the substrate. A p^+-a-Si:H was grown on the substrate. Subsequently, the superlattice structure (a-Si:H as well layers and a-SiC:H as barrier layers) was prepared by glow discharge deposition. The a-SiC:H barrier layers were deposited from silane (SiH_4) and methane CH_4) gases. The substrate temperature and gas pressure were 250°C and 1.0 torr, respectively. In order to avoid carbon contamination in the a-Si:H layer, the glow discharge was turned off at the end of each layer deposition, and the reaction chamber was purged by hydrogen gas for 5 min. The deposition rates of a-Si:H and a-SiC:H were 1.67 and 0.67 Å/s, respectively. Finally, a 500-Å n^+-a-Si:H and a 5000-Å Al layer were consecutively formed. The p^+-i-n^+ structure consists of 10 periods of undoped a-Si(200 Å)/SiC(280 Å):H superlattice between the p^+ and n^+ a-Si:H layers.

III. Impact Ionization Rates

Photocurrent multiplication measurements under pure electron injection can be obtained in the structure of Fig.

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1 by illuminating the p^+ layer from the transparent ITO layer. Measurements of pure hole injection, which is necessary to generate carriers in the n^+ layer, can be obtained in the structure consisting of glass/ITO/n^+-a-Si/i-SL/p^+-a-Si/Al. Photocurrent measurements as a function of reverse bias under pure electron and hole (inset) injection were performed using a 6328-Å He–Ne laser that was attenuated and focused on the center of the device. The photocurrent, which was synchronously detected by a lock-in amplifier, is plotted in Fig. 2 as a function of applied reverse bias. The scale on the right gives the dc multiplication factor M. The photocurrent increases gradually with reverse bias from a zero bias of 5 μA (0.15 μA) up to about 6 V (8 V) where photocurrent multiplication begins under pure electron (hole) injection conditions, respectively.

Ideally, the multiplication factor per stage is exactly 2; each carrier impact ionizes once after each band-edge step. In practice, the multiplication factor is $1 + r$, where r is the ionization yield (the fraction of carriers ionizing per stage). The total multiplication factor of the structure is then $M = (1 + r)^n$ [2], where n is the number of stages. At 14 V, the electron (r_e) and hole (r_h) ionization yields are 0.399 and 0.19, respectively.

Because the energy difference of the valence band edge ($\Delta E_v \sim 0.1$ eV) is very small [11] and the band discontinuity mainly leads to the energy difference of the conduction band ($\Delta E_c \sim 0.35$ eV) in the a-Si($E_g = 1.8$ eV)/SiC($E_g = 2.25$ eV):H heterostructure, it is expected that enhancement of the ionization rate ratio ($K = \alpha/\beta$) can be achieved. The ionization rates α and β were calculated with the well-known formulas for p-i-n diodes [12]

$$\alpha(E) = \frac{1}{w}\left[\frac{M_e(v) - 1}{M_e(v) - M_h(v)}\right] \ln\left[\frac{M_e(v)}{M_h(v)}\right]$$

and

$$\beta(E) = \frac{1}{w}\left[\frac{M_h(v) - 1}{M_h(v) - M_e(v)}\right] \ln\left[\frac{M_h(v)}{M_e(v)}\right]$$

where w the width of the superlattice region, V the applied reverse bias, and E the electric field calculated from $E = V/w$, respectively.

The ionization rates were calculated from electron and hole photocurrent multiplication data (shown in Fig. 2) using the above equations, and were plotted in Fig. 3. The data can be approximately expressed by the empirical expressions

$$\alpha(E) = 8.34 \times 10^4 \exp(-2.0998 \times 10^5/E)\text{cm}^{-1}$$

$$\beta(E) = 1.789 \times 10^4 \exp(-2.7910 \times 10^5/E)\text{cm}^{-1}$$

for electric fields E in volts per centimeter. The electron ionization rate is larger than β over the entire field range shown, with the ratio $K = \alpha/\beta$ decreasing from 6.5 to 5.05 as the field increases from 2.08×10^5 V/cm to 2.92×10^5 V/cm. This is the first observation of the ionization rate ratio K in an a-Si/SiC:H superlattice structure. A higher α to β ratio is achievable by tailoring the superlattice composition and thicknesses.

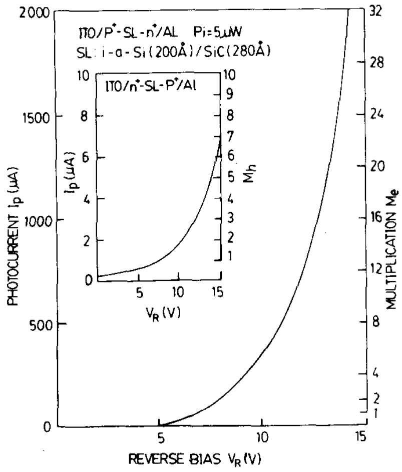

Fig. 2. Photocurrent–voltage characteristics and dc multiplication factor under a condition of pure electron injection (λ = 6328 Å). The inset shows the results for pure hole injection conditions.

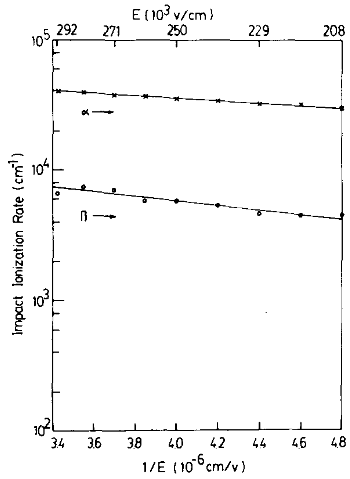

Fig. 3. Calculated carrier-impact ionization rate as a function of inverse applied electric field in the a-Si/SiC:H SAPD structure. An empirical parameterization of the data is also indicated.

The ionization rates obtained from the above I/V method give a first-order estimation only, which is caused by the difficulty in the separation of carriers, the source of carriers origination, etc. A more accurate means of measurement will be by the noise figure [8], [9] measurement in which noises originating from different mechanisms (e.g., injection or recombination) can be descriminated. However, due to the lack of such a setup presently, these data will be reported and be compared later.

IV. Device Characteristics

The simplified energy band diagram of the a-Si/SiC:H SAPD under normal operating conditions is shown in Fig.

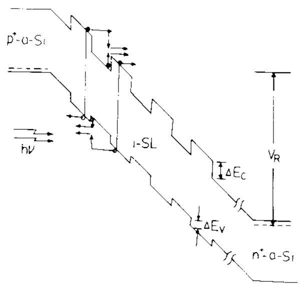

Fig. 4. Energy-band diagram of an a-Si/SiC:H superlattice avalanche photodiode (SAPD).

4. The device is designed in such a way that the central superlattice structure is completely depleted under thermal equilibrium. Normally, the device is operated under reverse bias, while an incident light signal is illuminated through the glass/ITO into the superlattice region. Fig. 5 shows the current–voltage characteristics for a typical device with different incident light power P_{in} as a parameter under illuminated and dark conditions. The device area is 1.41×10^{-2} cm^2. The photocurrent I_p is measured under the illumination of light from an He–Ne laser, where the optical power is attenuated by a variable beam splitter and is calibrated by a photometer. At low bias (<4 V), the collection efficiency is less than 1 due to the large rate of recombination of electrons and holes in the wells, as compared with the rate of thermionic emission of carriers from wells. The emission rate increases with electric field due to hot-carrier effects, and the photocurrent gradually increases from 4 to 10 V. At higher applied fields the photocurrent increases sharply, which indicates significant photocurrent multiplication. In general, the dc optical gain G can be defined as

$$G \equiv [(I_p - I_d)/q]/(P_{in}/h\nu)$$

where I_p is the photocurrent under illumination, I_d the dark current, P_{in} the incident light power, $h\nu$ the energy of the incident radiation, and q the electron charge. The typical SAPD exhibited an optical gain as high as 184, $I = 0.48$ mA, and $I_d = 10.3$ μA at $V_R = 20$ V under a P_{in} of 5 μW without antireflection coating. The dependence of G on illumination intensity can be shown in Fig. 6. The value of G increases with decreasing input power. Similar behavior has also been observed in previously reported photodetectors [13]–[16]. The optical gain increases with the reverse bias due to the impact ionization effects of the photogenerated carriers. It is found that the value of G of the ITO/p$^+$-SL-n$^+$ structure is larger than that of the ITO/n$^+$-SL-p$^+$ structure. The results of these measurements also give direct evidence that α is greater than β.

The capacitance value of 345 $\pm$ 5 pf is obtained by capacitance–voltage measurements, and is nearly constant with bias. The nearly constant capacitance with bias confirms the absence of depletion effects in the SAPD operation. According to $C = \epsilon_0 \epsilon_r A/d$, the dielectric constant ϵ_r is approximately the value of 13.26. In general, the switching time t_s, defined as $(t_{on} + t_{off})/2$, is related to the junction capacitance C and the load resistance R_L. For the values of $R_L = 1.8$ kΩ and $C = 345$ pf, the calculated t_s is 0.621 μs, which is lower than the measured value of 4.5 μs (see Fig. 7). The difference may be due to the stray capacitance and the series resistance of the device.

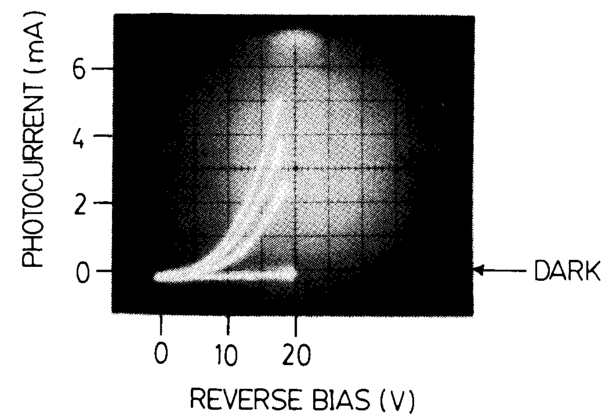

Fig. 5. Current–voltage characteristic generated by an He–Ne laser radiation under reverse-bias operation. The incident power levels are 0, 0.66, 1.33, and 2.0 mW, respectively.

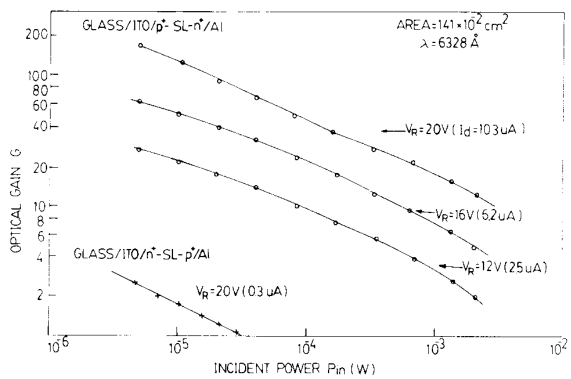

Fig. 6. The optical gain G versus incident optical power P under different reverse bias V_R as parameter.

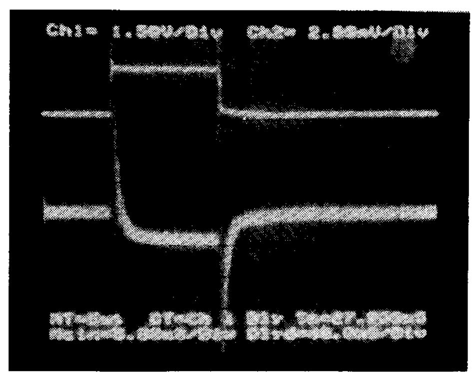

Fig. 7. Response of the a-Si/SiC:H SAPD to a LED light pulse. Upper trace: the input waveform; lower trace: the response waveform.

V. Conclusions

Photocurrent multiplication measurements have been performed on a-Si/SiC:H superlattice avalanche photodiodes under electron and hole injection conditions. Impact ionization rates calculated from the multiplication data from optimized devices indicate that the ratio of the electron to hole ionization rates is 6.5 in a field of 2.08 $\times 10^5$V/cm. Furthermore, we have demonstrated that high-gain SAPD's can be obtained by adding an a-Si/SiC:H superlattice structure in the photodiode. This device exhibited an optical gain as high as 184 under an incident optical power of 5 μW. The switching time of an LED-SAPD photocouple was measured to be 4.5 μs at $R_L = 1.8$ kΩ. Based on the measured results of the study, the SAPD is promising in producing a high-sensitivity and high-frequency switching control system.

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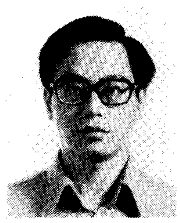

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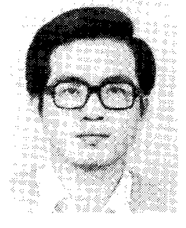

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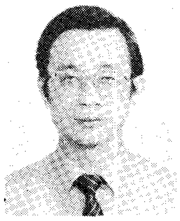

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