# Optical and Noise Characteristics of Amorphous Si/SiC Superlattice Reach-Through Avalanche Photodiodes

JYH-WONG HONG, WUU-LARNG LAIH, YU-WEN CHEN, YEAN-KUAN FANG,
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*Abstract*—**In order to improve the performance of the a(amorphous)-Si:H/SiC:H superlattice APD (SAPD), the a-Si:H/SiC:H superlattice reach-through APD's (SRAPD's) have been fabricated on ITO(indium tin oxide)/glass substrates by plasma-enhanced chemical vapor deposition (PECVD). For a typical electron-injection SRAPD, the ratio of room-temperature electron and hole impact ionization rates ($\alpha/\beta$) is 10.2 at an electric field $3.33 \times 10^6$ V/cm as determined by the photocurrent multiplication measurement and checked by the excess noise factor test, the optical gain is 506 at an applied reverse-bias $V_R = 18$ V and an incident power $P_{in} = 5$ μW emitted from a He-Ne laser, the rise time is 1 μs at a load resistance $R_L = 1$ kΩ, and the excess noise factor is 6.53 at a multiplication $M = 48$. These results are better than those of the other amorphous photodetectors ever reported. Some performances of homojunction a-Si:H reach-through APD's (RAPD's) is also described for the purpose of comparison.**

## I. INTRODUCTION

RECENTLY, many III-V compound superlattice and multilayer APD's with different structures have been studied theoretically and experimentally [1]–[6], and some characteristics of the first a-Si:H/SiC:H superlattice APD (SAPD) with step-like multilayer barriers made of noncrystalline material have also been reported [7]. In these devices, the energy-band barriers formed by wide-gap material are used to spatially confine the carrier ionizations within the narrow-bandgap material which forms the wells. If the applied reverse-bias voltage across the well is sufficiently greater than the barrier potential to let the carriers in the well have enough average kinetic energy to surmount the barrier, the carriers can traverse the wide-gap material and gain a kinetic energy equal to the bandgap discontinuity after crossing the next downward barrier. The net effect is that the impact ionization threshold energy of the narrow-bandgap material is reduced by an amount equal to the barrier energy, and the effective impact ionization rate is enhanced since it increases exponentially with the decreased ionization threshold energy [8].

The signal-to-noise power ratio of an APD or RAPD can be improved when the excess noise due to the avalanche process is minimized by the very dissimilar impact-ionization rates for electrons and holes, and initiating the avalanche process with the carrier species having higher impact-ionization rate [9]–[11]. For an a-Si:H ($E_g \sim 1.8$ eV)/SiC:H ($E_g \sim 2.25$ eV), the conduction band-edge offset ($\Delta E_c \sim 0.35$ eV) is substantially larger than the valence band-edge offset ($\Delta E_v \sim 0.1$ eV) [12] so it is expected and proven that the electron ionization rate $\alpha$ is larger than the hole ionization rate $\beta$ and the device structure can be tailored to provide the nearly pure electron injection [7].

To improve the performance of the a-Si:H/SiC:H SAPD, the reach-through structure previously described by Ruegg [13] is adopted and modified with its high-field avalanche region replaced by an a-Si:H/SiC:H superlattice multilayer. This proposed a-Si:H/SiC:H superlattice reach-through APD (SRAPD) has several desirable features. The tradeoff between the quantum efficiency and the speed of response can be accurately controlled by changing the thickness of the low-field intrinsic absorption and drift region. The wide low-field region in the RAPD structure also provides a much more gradual change in the avalanche gain with applied bias voltage. The avalanche gain can be adjusted independently, since the avalanche multiplication predominantly occurs in the narrow high-field region. So, the proposed a-Si:H/SiC:H SRAPD is expected to have high optical gain, high response speed, and a good signal-to-noise ratio [14].

## II. DEVICE STRUCTURE AND FABRICATION

Fig. 1 shows the schematic cross section of an electron-injection a-Si:H/SiC:H SRAPD. An ITO-coated Corning 7059 glass plate was used as the substrate. The 200-Å p$^+$-type a-Si:H layer, 4000-Å undoped a-Si:H layer, 100-Å lightly doped p-type a-Si:H layer, the intrinsic superlattice structures of 3–6 periods (80-Å a-SiC:H as the barrier layer and 100-Å a-Si:H as the well layer), and then a heavily doped n$^+$-type a-Si:H layer were de-

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Manuscript received September 8, 1989; revised February 5, 1990. Part of this work was supported by the National Science Council, Republic of China. The review of this paper was arranged by Associate Editor G. Craford.

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IEEE Log Number 9035774.

0018-9383/90/0800-1804$01.00

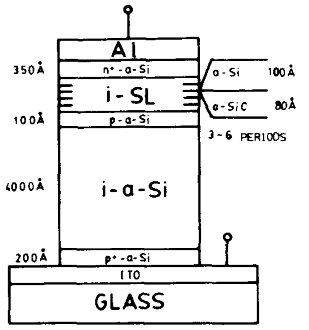

Fig. 1. The schematic cross section of the electron-injection a-Si : H/SiC : H superlattice reach-through APD (SRAPD).

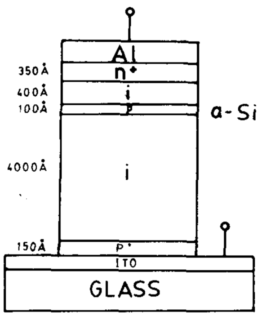

Fig. 2. The schematic cross section of the electron-injection homojunction a-Si : H reach-through APD (RAPD).

posited by using a PECVD system. Finally, a 5000-Å Al layer was deposited onto the $n^+$-type a-Si : H layer by thermal evaporation and used as the contact electrode. The deposition rates of a-Si : H and a-SiC : H layers were 1.67 and 0.67 Å/s, respectively. The device area is $1.42 \times 10^{-2}$ cm$^2$. The substrate temperature and gas pressure were 250°C and 1.0 torr individually. In order to avoid carbon contamination in the a-Si : H layer, the glow discharge was turned off at the end of each a-SiC : H layer deposition, the reactive gases in the chamber were completely pumped out, and the reaction chamber was purged by hydrogen gas for 5 min prior to the deposition of the next a-Si : H layer.

For the purpose of performance comparison, a homojunction electron-injection a-Si : H RAPD with similar device dimensions illustrated in Fig. 2 was also fabricated by using the same process conditions. The hole-injection a-Si : H/SiC : H SRAPD and a-Si : H RAPD with complementary structures were fabricated too to obtain the hole multiplication factors.

All of the above RAPD's were designed in such a way that the 100-Å lightly doped p-type a-Si : H layer was thin enough to let the electric field extend all the way from the high-field avalanche region to low-field intrinsic absorption region at any operating voltage, i.e., at a voltage greater than or equal to the reach-through bias voltage $V_{RT}$ which is below the breakdown voltage of the high-field region. The applied voltage in excess of the $V_{RT}$ was dropped across the low-field region with a thickness of 4000 Å which is optimal for device performance. The absence of depletion effects in the above RAPD and SRAPD operations was confirmed by the nearly constant capacitance values obtained by the capacitance–voltage measurements. It was also expected that the carriers could travel at their saturation velocity in the low-field region to obtain a high response speed.

The energy-band diagram of the electron-injection a-Si:H/SiC:H SRAPD under reverse-bias condition is shown in Fig. 3. The fully depleted structure allows the device to be used with incident light entering the $p^+$ contact. The electrons generated in the low-field absorption region are swept to the high-field avalanche region, the generated holes traverse the low-field absorption region to the $p^+$ contact, and thus constitute the total multiplied current.

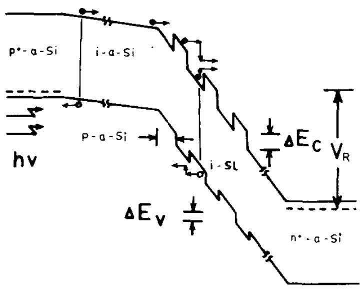

Fig. 3. The energy-band diagram of the electron-injection a-Si : H/SiC : H SRAPD.

## III. Impact Ionization Rates and Excess Noise Factors

Fig. 4 illustrates the electron multiplication factors *M*'s versus the applied reverse-bias $V_R$ for electron-injection a-Si : H/SiC : H SRAPD with three periods of superlattice and a-Si : H RAPD. The *M* was calculated by linearly extrapolating the low-bias data of primary (unmultiplied) photocurrent to the high-bias values and taking the ratio of the difference of the multiplied photocurrent and dark current which is usually negligible to the linearly extrapolated primary photocurrent at certain reverse-bias voltage [15]. The photocurrent measurements were performed by using a 6328-Å He–Ne laser that was attenuated and focused on the center of the device with incident power $P_{\text{in}} = 5\ \mu$W. The photocurrent was synchronously detected by using a lock-in amplifier. It can be seen from the figure that the electron multiplication factors increase relatively slowly with increasing reverse bias above certain voltages. These voltages could be the $V_{RT}$'s of the devices. The electron multiplication factor of the a-Si : H/SiC : H SRAPD is generally higher than that of the a-Si : H RAPD. Similarly, the hole multiplication factors were obtained from the complementary devices.

Since the avalanche process predominantly occurs in the high-field region, the impact ionization rates $\alpha$ and $\beta$ for a-Si : H RAPD is estimated from the electron and hole multiplication factors using the well-known formulas for

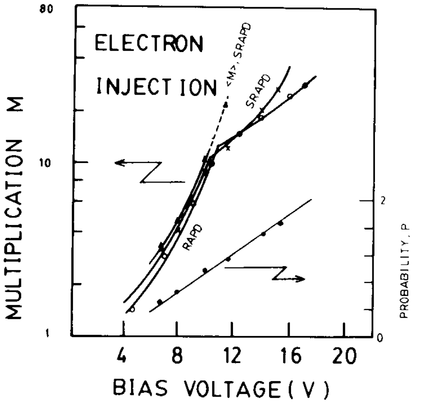

Fig. 4. The multiplication factors versus applied reverse-bias voltage for electron-injection a-Si : H/SiC : H SRAPD and a-Si : H RAPD. The average multiplication $\langle M \rangle$ and electron impact ionization probability per dynode $P$ for a-Si : H/SiC : H SRAPD are shown also.

p-i-n diodes [16]. In a-Si:H/SiC:H SRAPD, the avalanche region can be assumed to be only in a-Si:H well layers, because the ionization threshold energies which are roughly proportional to the bandgap are much higher in a-SiC:H barriers than in a-Si:H wells. Then, the average $\alpha$ and $\beta$ [3], [17] can be obtainable by these formulas as well. The obtained impact-ionization rates are plotted in Fig. 5 as a function of electric field $E \sim V_R/W$, where $W$ is the width of the high-field region, for a-Si:H/SiC:H SRAPD and a-Si:H RAPD. The electron ionization rate $\alpha$ is larger than the hole ionization rate $\beta$ over the entire field range. The data for a-Si:H/SiC:H SRAPD can be expressed approximately by the empirical expressions

$$\alpha(E) = 1.14 \times 10^6 \exp(-2.05 \times 10^6/E)\ \mathrm{cm}^{-1}$$

$$\beta(E) = 1.66 \times 10^5 \exp(-3.95 \times 10^6/E)\ \mathrm{cm}^{-1}$$

where electric field $E$ is in volts per centimeter. The impact ionization rate ratio ($K = \alpha/\beta$) is 10.02 at an electric field of $3.33 \times 10^6$ V/cm for a-Si:H/SiC:H SRAPD, and that for a-Si:H RAPD is 6.95 at the same electric field.

To verify the obtained ratio $K = \alpha/\beta$, the excess noise factor [9] was calculated for electron-injection a-Si:H/SiC:H SRAPD from the noise spectral density measurements under dark and illuminated ($P_{\mathrm{in}} = 5\ \mu$W) conditions. In noise measurement, the reverse-biased device was illuminated by a chopped 6328-Å He-Ne laser and the photocurrent was determined by a lock-in amplifier. The component of the signal which varied synchronously with the photocurrent was measured by using another lock-in amplifier and displayed on a dynamic signal analyzer. In this way, the locked-in output, which was proportional to the photocurrent noise power, could be averaged over a long time interval. Since the shot noise is the dominant one, using the common expressions of noise spectral densities under dark and illuminated conditions for an APD, and employing the known primary photocurrent and multiplication factor, the excess noise factor can be determined. The data of noise spectral densities were taken at a frequency of 40 kHz, which avoided the increase of noise in lower frequency range. For electron injection alone, in terms of McIntyre's theory [9], the excess noise factor $F$ can be written as

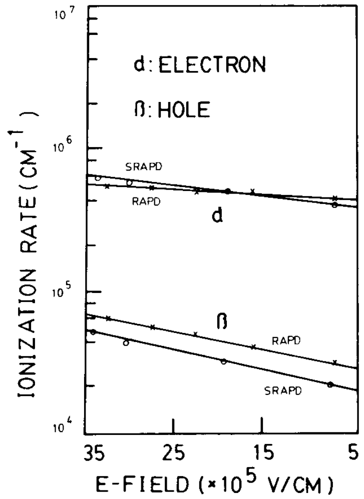

Fig. 5. The calculated impact ionization rates for electron and hole as a function of decreasing electric field in the a-Si : H/SiC : H SRAPD and a-Si : H RAPD structures.

$$F = K'M + (2 - 1/M)(1 - K')$$

where $K' = 1/K$, hence one can find the impact ionization rate ratio $K$ from the calculated $F$ and the known $M$. The obtained $K$ is 11.29 which is approximately the same as the one (10.02) obtained from the photocurrent multiplication method.

The excess noise factors calculated by using the above equation as a function of the multiplication factor at a fixed $K$ = 10.02 and 6.95, respectively, for a-Si:H/SiC:H SRAPD and a-Si:H RAPD are shown in Fig. 6. The data for the typical crystalline Si (c-Si) RAPD are also included for comparison [8]. The excess noise factor is 6.53 for a-Si:H/SiC:H SRAPD at $M$ = 48, and 6.47 for a-Si:H RAPD at $M$ = 33.5. The $F$ value is also affected by the width of high-field avalanche region at a fixed operating bias. Experimentally, we found that the $K$ value increased and $F$ value decreased with the increasing width of the high-field avalanche region.

Explicit formulas for the excess noise factor $F_e$ and average multiplication $\langle M \rangle$ in double-carrier SAPD with electron injection, assuming the electron impact ionization probability per dynode is less than one, were presented by Teich *et al.* [19, eqs. (25) and (27)]. The electron impact ionization probability per dynode

$$P = \exp\left(\int_0^L \alpha\, dz\right) - 1$$

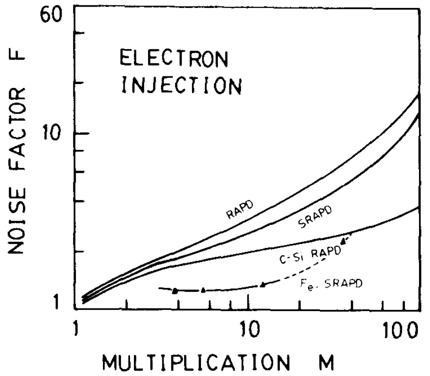

Fig. 6. The calculated excess noise factors as a function of multiplication factor for electron-injection a-Si : H/SiC : H SRAPD, a-Si : H RAPD, and c-Si RAPD. The estimated $F_e$ for a-Si : H/SiC : H SRAPD is shown as well.

where $L$ is the length of each dynode. Using the average $\alpha$ and $\beta$ shown in Fig. 5 for a-Si : H/SiC : H SRAPD, the $F_e$ and $\langle M \rangle$ estimated by employing those two equations are shown in Figs. 4 and 6, respectively. For the dash portions of curves in the figures, the calculated electron impact ionization probability per dynode $P$ is greater than one as shown in Fig. 4. The estimated $\langle M \rangle$ for a-Si : H/SiC : H SRAPD is slightly larger than $M$ in the low bias range ($P < 1$), where [19, (27)] is applicable. The difference between $F$ and $F_e$ for the a-Si : H/SiC : H SRAPD is about 0.6–2.8. These discrepancies could be due to the fact that a-Si : H/SiC : H SRAPD has a high electron impact ionization probability (here $P$ is larger than 1, thus [19, (27)] becomes invalid) which can lead to improved multiplication and increased excess noise factor [20]. Theory of McIntyre is applied by considering the continuous multiplication region and was shown as $F$ in Fig. 6.

## IV. OPTICAL CHARACTERISTICS

Generally, the dc optical gain $G$ for above devices can be defined as

$$G \equiv [(I_{\mathrm{PH}} - I_D)/q]/(P_{\mathrm{in}}/h\nu)$$

where $I_{\mathrm{PH}}$ is the photocurrent under illumination, $I_D$ the dark current, $P_{\mathrm{in}}$ the incident light power, $h\nu$ the energy of the incident radiation, and $q$ the electron charge. Fig. 7 shows the dependence of optical gain $G$ on the incident power for three device structures, i.e., a-Si : H/SiC : H SRAPD with three periods of superlattice, a-Si : H RAPD, and a-Si : H/SiC : H SAPD [7]. Without antireflection coating, the a-Si : H/SiC : H SRAPD exhibited an optical gain of 506 when $V_R = 18$ V, $I_{\mathrm{PH}} = 1.293$ mA, $I_D = 9.21$ $\mu$A, and $P_{\mathrm{in}} = 5$ $\mu$W, and that for a-Si : H RAPD is 380 when $V_R = 14.5$ V, $I_{\mathrm{PH}} = 0.97$ mA, $I_D = 10.7$ $\mu$A, and $P_{\mathrm{in}} = 5$ $\mu$W also. The $G$ value increases with decreasing incident power, which is a unique feature of majority-carrier photodetectors. Similar behavior has also been observed in previously reported photodetectors [21]–[25]. The optical gain $G$ of the a-Si : H/SiC : H SRAPD is the highest one among those reported. The optical gain of a-Si : H RAPD is also higher than that of a-Si : H/SiC : H SAPD [7]. It was also found experimentally that the optical gain increased with the reverse bias due to the higher impact ionization rates of the photogenerated carriers. The optical gain and breakdown voltage of the a-Si : H/SiC : H SRAPD also increased with the well thickness when it was varied from 80 to 120 Å. But the optical gain decreased if the number of superlattice periods is increased from 3 to 6. Increasing the well thickness will increase the electron energy by increasing its drift length. This can increase the impact ionization probability, which in turn increases the optical gain. But, when the well thickness or number of period is increased over a certain limit, the resulting reduction of high electric field in the undoped superlattice region reduces the obtainable optical gain.

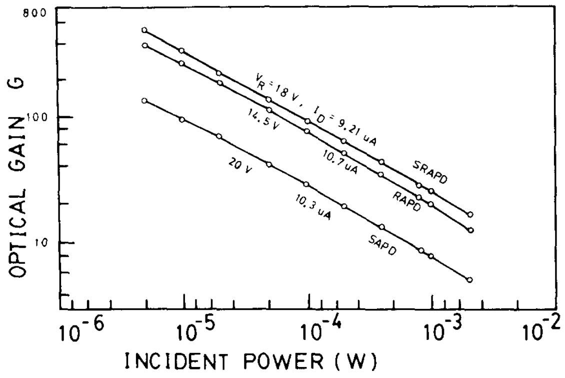

Fig. 7. The optical gain $G$ versus incident He–Ne laser power $P_{\mathrm{in}}$ for a-Si : H/SiC : H SRAPD, a-Si : H RAPD, and a-Si : H/SiC : H SAPD.

The photo-response speed was measured by illuminating the device with the light pulse emitted from a commercial red LED (with a response time of 90 ns) and monitoring the waveform of the photocurrent. The device was in series with a variable load resistor $R_L$. The switching time $t_s$, defined as $(t_{\mathrm{on}} + t_{\mathrm{off}})/2$, generally is related to the product of the junction capacitance and the load resistance $R_L$, and is also increased by the stray capacitance and series (contact and internal) resistance of the device. The measured rise times ($t_{\mathrm{on}}$'s) for both the electron-injection a-Si : H/SiC : H SRAPD and a-Si : H RAPD were about 1 $\mu$s at $R_L = 1$ k$\Omega$.

## V. CONCLUSION

The performance of the electron-injection a-Si : H/SiC : H reach-through APD (SRAPD) has been characterized by using the photocurrent multiplication measurements and by the excess noise factor measurements. The empirical expressions for electron and hole ionization rates are obtained. The excess noise factor of the device is a little higher than that obtained from the formula presented by Teich *et al.* [19]. This discrepancy could be due to high electron impact ionization probability in well layers of this device. From the results of this study, it is seen that the a-Si:H/SiC:H SRAPD is a promising device for photodetector application.

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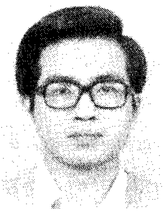

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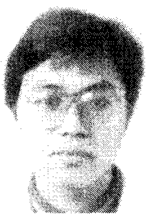

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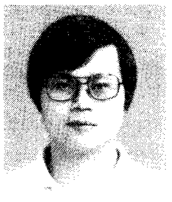

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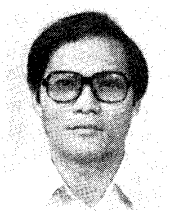

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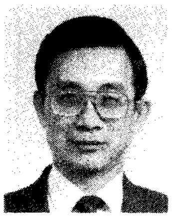

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