The Hydrogenated Amorphous Silicon Reach-Through Avalanche Photodiodes (a–Si : H RAPD's)

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Abstract—**The RAPD structure is adopted to improve the electrical and optical performance of the photosensing device made of a–Si : H. Both the electron-injection n^+–i–δp–i–p^+ and hole-injection p^+–i–δn–i–n^+ a–Si : H RAPD's are fabricated on the ITO-coated glass substrates by plasma enhanced chemical vapor deposition (PECVD) system. The photocurrent multiplication method is employed to study the multiplication factors and the impact ionization coefficients of the a–Si : H RAPD's. Since the electron-injection models have better performance, the relationships between the device dimensions and characteristics, such as *I–V* curves, optical gains, impact ionization rates, and excess noise factors are further studied and presented. An optical gain of 380 can be obtained under a 5 μW He–Ne laser input light power and at a reverse-bias voltage of 14.5 V. The excess noise factor is 6.47 at a multiplication of 33.46. The dynamic rise time of 1 μs has been observed under a 1.8 kΩ load resistance. The hole and electron impact ionization rates (β and α) can be expressed empirically by $\beta(E) = 9.87 \times 10^4 \exp(-1.36 \times 10^6/E)$ cm^{-1} and $\alpha(E) = 6.34 \times 10^5 \exp(-3.16 \times 10^5/E)$ cm^{-1} for electric field E ranging from 5×10^5 to 3.5×10^6 V/cm, respectively. Based on the results of this paper, the a–Si : H RAPD would be a promising a–Si : H device for the photosensing applications.**

I. Introduction

RECENTLY, several new photosensing devices made of amorphous films, such as the a–Si : H phototransistors [1]–[5], the heterojunction a–Si : H/a–SiC : H phototransistors [6], [7], and the a–Si : H/a–SiC : H superlattice avalanche photodiodes (APD's) [8], have been investigated. These phototransistor structures are essentially an amorphous n–i–p–i–n multilayer. The photocurrent amplification of the phototransistors is due to an induced barrier lowering at the base by the photogenerated holes, and this barrier lowering enhances the thermionic emission of electrons from emitter to collector in turn [9]. The photocurrent multiplication by impact ionization can also be used to obtain signal amplification, and is demonstrated by the reported a–Si : H/a–SiC : H superlattice APD [8]. The superlattice APD is made of step-like multilayers which form heterojunction potential barriers to spatially confine the carrier ionizations within the narrow band-gap material. In this way, the ionization rate can be enhanced. Since, in the heterobarriers of a–Si : H/a–SiC : H superlattice APD, the conduction band edge offset is larger than the valence band edge offset, it is seen that the electron impact ionization rate α is enhanced more than the hole impact ionization rate β. This dissimilar α and β can reduce the excess noise factor which is contributed from the avalanche process initiated by the electron injection [8].

Since the low-temperature ($\sim 230°$C) deposition of the a–Si : H film possesses a very abrupt change of doping profile which is impossible in single-crystalline material, the structure of a reach-through APD (RAPD), first described by Ruegg [10], is adopted and implemented with a–Si : H films. An a–Si : H RAPD has an n^+–i–δp–i–p^+ electron-injection structure. This structure has several desirable characteristics not present in the other structures. The tradeoff between the quantum efficiency and response speed can be accurately controlled by adjusting the width of the low-field absorption region. Photocurrent multiplication occurs primarily in the narrow high-field avalanche region. The wide, low-field drift region in the device produces a much more gradual change in the multiplication with reverse bias voltage, which is desirable for practical applications. In addition, the device structure may provide nearly pure electron injection regardless of the wavelength of the incident light, and since the electron has a higher impact ionization rate, good noise performance of the device is obtainable [11].

In this paper, both a–Si : H electron-injection (n^+–i–δp–i–p^+) and hole-injection (p^+–i–δn–i–n^+) RAPD's fabricated on ITO coated glass substrates by using the PECVD system are described. Since the hole-injection structure has poor performance as expected, its properties are included only for comparison and calculating the hole multiplication factor. The optical and noise performance, and the *I–V* characteristics of the electron-injection a–Si : H RAPD's with different device dimensions are described and discussed.

II. Device Structure and Fabrication

Fig. 1(a) shows a cross-sectional view of the device of the electron-injection a–Si : H RAPD. The device area is 1.41×10^{-2} cm^2. The high-field undoped i-layer has a

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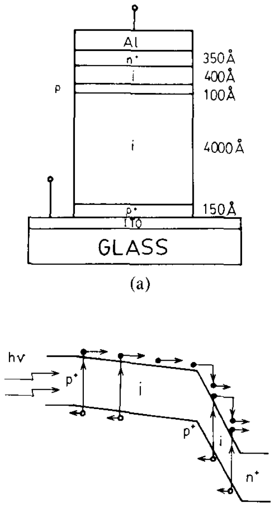

(a)

(b)

Fig. 1. The schematic diagram for (a) cross-sectional view, and (b) energy-band of electron-injection a-Si : H RAPD.

width of 400 Å normally as shown in the figure unless otherwise noted. The width of this i-layer is adjusted from 200 to 1000 Å in order to observe its effect on the device performance. The 4000 Å width of the low-field absorption undoped i-layer region is chosen to be larger than the penetration depth of the incident light, so that pure electron injection can be obtained. The 100 Å lightly-doped p-layer is thin enough to let the electric field extend all the way from the high-field avalanche region to the low-field absorption region at an operating voltage greater than or equal to the reach-through voltage V_{RT} which is smaller than the breakdown voltage of the high-field avalanche region. The applied voltage in excess of the V_{RT} is dropped across the low-field absorption region. It is also expected that the electrons could travel at their saturation velocity in the low-field absorption region to obtain a short switching time. The nearly constant capacitance obtained by *C–V* measurement near the bias point confirms the absence of the depletion effect in the RAPD.

Fig. 1(b) illustrates the energy-band diagram of the device under reverse bias. Radiation is incident onto the glass substrate and penetrates into the low-field absorption region. The electrons photogenerated in the low-field absorption region are swept to the high-field avalanche region, where the impact ionization occurs. The photogenerated holes traverse the low-field region to the p^+ contact. The holes generated by the electron impact ionization are presumed to have a low impact ionization rate and drift to the p^+ contact as well.

The deposition conditions of various a-Si : H films were the same as those described in the previous reports [1]–[5]. The 5000 Å Al metal film was deposited by using a thermal evaporator. The device is without antireflection coating on the glass surface. After fabrication, the device was packaged in a suitable fixture for various tests.

III. Device Characteristics

I–V Curves

The *I–V* curves of the a-Si : H RAPD under dark, low, medium, and high incident light power are shown in Fig. 2. The light source is a He–Ne laser and the laser beam intensity is controlled by a variable beam splitter and calibrated by a photometer. The width of the avalanche region is 400 Å for the tested device. The avalanche effect can be clearly seen, since the photocurrent increases sharply for the reverse bias near the breakdown voltage. The photocurrent increases relatively slowly for the low bias range and the dark multiplied current is small.

Fig. 3 illustrates the photocurrent as a function of the reverse bias voltage with the avalanche-region width as the parameter. The thinner the avalanche-region width is, the larger the photocurrent obtained, since, at the same reverse bias voltage, the higher electric field in the thinner avalanche-region width causes a higher avalanche multiplication. The photocurrent increases noticeably and the breakdown voltage decreases as the avalanche-region width decreases. The normal 400 Å width of the avalanche-region is based on the tradeoff between the breakdown voltage and the obtainable photocurrent.

Optical Gain

Generally, the dc optical gain of the device can be defined as

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

where I_{PH} is the photocurrent under illumination, I_D is the dark current, P_{in} is the incident light power, $h\nu$ is the energy of the incident radiation, and q is the electron charge.

Fig. 4 shows the optical gain as a function of incident light power P_{in} at different dark current for the a-Si : H RAPD. An optical gain of 380 at $P_{in} = 5$ μW, $V_R = 14.5$ V, $I_D = 10.8$ μA is obtainable. The optical gain depends on the reverse bias and the incident light power. The optical gain increases with increasing dark current (or reverse bias). For the hole-injection a-Si : H RAPD with complementary structure, the optical gain is approximately equal to one hundredth of that obtained for the electron-injection a-Si : H RAPD at the same test conditions.

Increasing the width of avalanche region reduces the optical gain at a fixed dark current $I_D = 10$ μA, as shown in Fig. 5, since the electric field in the high-field avalanche region is reduced as its width is increased.

All of the curves of the optical gain at a certain bias condition decrease with increasing incident light power; this is an unique feature of the majority-carrier photodetectors [12].

Spectral Response

The spectral response was measured by illuminating the glass side of the device with a light beam emitted from tungsten lamp through a monochrometer. Fig. 6 shows the relative spectral response of the a-Si : H RAPD. Every

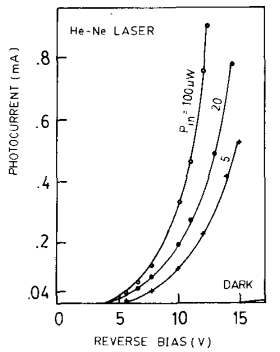

Fig. 2. The photo I-V curves of electron-injection a-Si : H RAPD's under various illumination levels.

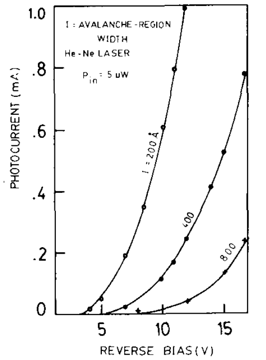

Fig. 3. The photocurrent versus reverse bias for electron-injection a-Si : H RAPD's with various widths of avalanche region.

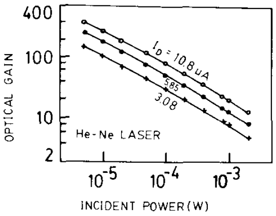

Fig. 4. The optical gain versus incident light power for electron-injection a-Si : H RAPD's at various bias conditions.

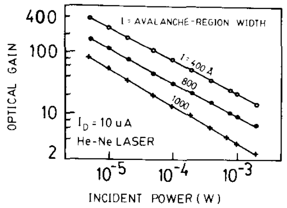

Fig. 5. The optical gain versus incident light power for electron-injection a-Si : H RAPD's with various widths of avalanche region.

curve in the figure is normalized to the incident light power of each wavelength. This relative response covers the wavelength from 420 to 780 nm. The spectral FWHM was measured to be about 200 nm. The peak wavelength of the relative spectral response shifts with reverse bias

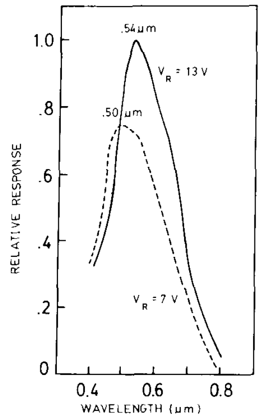

Fig. 6. The relative spectral response of electron-injection a-Si : H RAPD's at various bias voltages.

V_R. When $V_R = 7$ V, the peak response occurs at 500 nm wavelength. The peak response shifts to 540 nm wavelength gradually as V_R is increased to 13 V. For this RAPD device structure, since the light with longer wavelength can be absorbed at a deeper region away from the glass surface and near to the high-field avalanche region, so the spectral response of light with longer wavelength is enhanced by the avalanche effect when the reverse bias is increased.

Dynamic Response Speed

The photoresponse speed was measured with a red-LED-RAPD photocoupler with a variable load resistance by monitoring the waveform of the photocurrent. The speed of response depends on the load resistance, internal resistance, junction capacitance, etc. Since the junction capacitance of this device is very small due to having a wide depletion region, the a-Si:H RAPD can provide high-speed performance. The measured rise time is about 1 μs with a load resistance of $R_L = 1$ kΩ and increases to 6 μs if the $R_L = 10$ kΩ. This is the highest response speed reported for an amorphous photosensing device.

Multiplication

The multiplication factor was calculated by linearly extrapolating the low-bias data of the dark current to the high-bias values and taking the ratio of the observed photocurrent to the linearly extrapolated dark current at a certain reverse-bias voltage [13]. The incident light power emitted from the He-Ne laser was 5 μW. The calculated electron multiplication factor versus the reverse bias is shown in Fig. 7. The electron multiplication factor increases relatively slowly as the reverse-bias voltage exceeds a certain voltage (around 11 V). This voltage would be the reach-through voltage V_{RT} of the device, since the width of the low-field absorption region is larger and this, in turn, reduces the increasing rate of electric field with the applied reverse bias. The hole multiplication factor was obtained from the complementary device by using the same procedures.

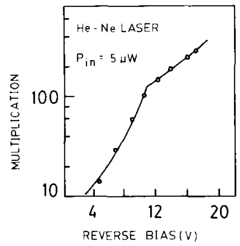

Fig. 7. The electron multiplication factor versus reverse-bias for an electron-injection a-Si : H RAPD.

Impact Ionization Rate

Since the RAPD structures can provide very pure electron or hole injection, the well-known formula for the p-i-n diodes to derive α and β from the electron and hole multiplication factors [14] can be used to obtain α and β for the a-Si : H RAPD as a function of electric field which is approximately equal to V_R/W, where V_R is the applied reverse bias and W is the width of avalanche region. The impact ionization rate ratio $K = \beta/\alpha$ can be obtained consequently.

Fig. 8 shows α and β versus the electric field for the a-Si:H RAPD. α is larger than β over the entire field range. The data of α and β can be fit to the theoretical results presented by Wolff [15] approximately by

$$\alpha(E) = 6.34 \times 10^5 \exp(-3.16 \times 10^5/E)$$

$$\beta(E) = 9.87 \times 10^4 \exp(-1.36 \times 10^6/E).$$

Excess Noise Factor

For electron injection alone, in terms of McIntyre's theory [16], the excess noise factor can be expressed by

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

For hole injection alone, the above equation still applies if K is replaced by $1/K$. The ratio K is assumed to be constant through the avalanche region.

Fig. 9 shows the ratio K and excess noise factor F at $M = 10$ as a function of the avalanche-region width for the electron-injection a-Si:H RAPD. The relation between the ratio K and the width of the avalanche region W can be understood by the breakdown condition [17]

$$\ln K/(K-1) = \alpha W.$$

The ratio K decreases as the width W increases. The excess noise factor F at $M = 10$ decreases when the width of avalanche region W increases, since the ratio K decreases.

The calculated excess noise factor as a function of multiplication with ratio K as a parameter is shown in Fig. 10. The ratios $K = 0.143$, 0.098, and 0.078 correspond to the avalanche-region widths $W = 40$, 60, and 80 nm, respectively. Clearly, increasing the width of avalanche region can reduce the excess noise at a certain multiplication level. The curve for $K = 0.143$ can be written as $F(M) \simeq M^{0.55}$.

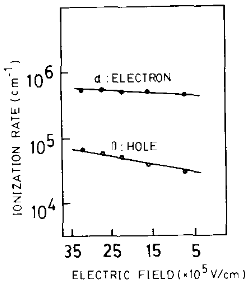

Fig. 8. The ionization coefficients versus the electric field for a-Si : H RAPD's.

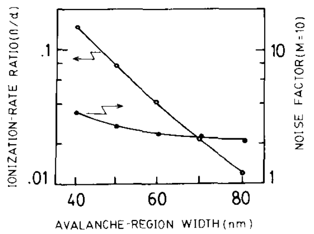

Fig. 9. The impact ionization rate ratio (β/α) and the excess noise factor (at $M = 10$) versus the width of avalanche region for electron-injection a-Si : H RAPD's.

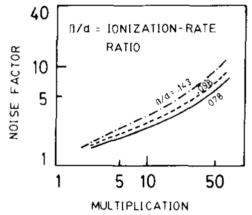

Fig. 10. The excess noise factor versus electron multiplication with different β/α ratio as parameter.

IV. Conclusions

An electron-injection a-Si : H RAPD has demonstrated high optical gain, fast response speed, and a low excess noise factor and is a promising amorphous photodetector. The voltage-dependent characteristics of its relative spectral response will provide a wide range of flexibility in developing a photosensing device with wavelength selectivity, like a voltage-controlled color sensor. The higher optical gain under lower illumination level makes it a very sensitive amorphous photosensor for low-level light detection.

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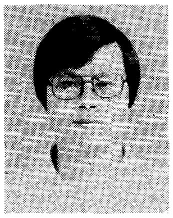

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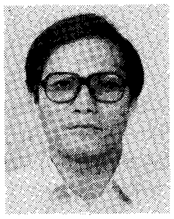

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C. Gong, photograph and biography not available at the time of publication.