Article:

Ng, B.K., Yan, F., David, J.P.R. et al. (4 more authors) (2002) Multiplication and excess noise characteristics of thin 4H-SiC UV avalanche photodiodes. IEEE Photonics Technology Letters, 14 (9). pp. 1342-1344. ISSN 1041-1135

https://doi.org/10.1109/LPT.2002.801112

Multiplication and Excess Noise Characteristics of Thin 4H–SiC UV Avalanche Photodiodes

B. K. Ng, F. Yan, J. P. R. David, R. C. Tozer, G. J. Rees, C. Qin, and J. H. Zhao

***Abstract*—The avalanche multiplication and excess noise characteristics of thin 4H–SiC avalanche photodiodes with an i-region width of 0.1 μm have been investigated. The diodes are found to exhibit multiplication characteristics which change significantly when the wavelength of the illuminating light changes from 230 to 365 nm. These multiplication characteristics show unambiguously that $\beta > \alpha$ in 4H–SiC and that the β/α ratio remains large even in thin 4H–SiC diodes. Low excess noise, corresponding to $k = 0.1$ in the local model where $k = \alpha/\beta$ for hole injection, was measured using 325-nm light. The results indicate that 4H–SiC is a suitable material for realizing low-noise UV avalanche photodiodes requiring good visible–blind performance.**

***Index Terms*—4H–SiC, avalanche multiplication, excess noise, impact ionization, photodiodes, UV APD, visible–blind.**

SILICON carbide (SiC) is an attractive material for optical detection in the UV regime owing to its wide bandgaps. SiC photodiodes should have the advantage of very low-dark current, the ability to operate at high temperature, and good visible–blind performance. The material quality of SiC has improved significantly over the last few years and a recent report of widely disparate ionization coefficients [1] suggests that it would be suitable for low excess noise avalanche photodiodes (APDs). In optical receivers limited by weak optical signals and high postamplifier noise, thin APDs can greatly enhance the signal-to-noise ratio by providing internal gain while maintaining a high-operating speed and a low-operating voltage. In this letter, we report the avalanche characteristics of thin 4H–SiC APDs with an i-region width of 0.1 μm. The responsivity at unity gain is measured over the wavelength range of 230–375 nm. Photomultiplication characteristics using UV light of variable wavelengths to alter the carrier injection conditions are presented and discussed. The excess avalanche noise characteristics of the APDs at a wavelength of 325 nm are also reported.

The APD structure comprises a 2 μm n layer, a thin i-region, a 0.2-μm p-layer, and a thin 0.1-μm p^+ cap grown on an n^+ 4H–SiC substrate. The intended doping levels in the n, p, and p^+ layers were 3×10^{18} cm^{-3}, 2×10^{18} cm^{-3}, and 4×10^{19} cm^{-3} respectively. Square mesa diodes with areas ranging from 60×60 μm^2 to 210×210 μm^2 were fabricated using a 2° positive bevel edge termination technology [2]. Windows were formed on the top ohmic contacts to provide optical access and a thin layer of SiO_2 and Si_3N_4 was used to passivate the diodes.

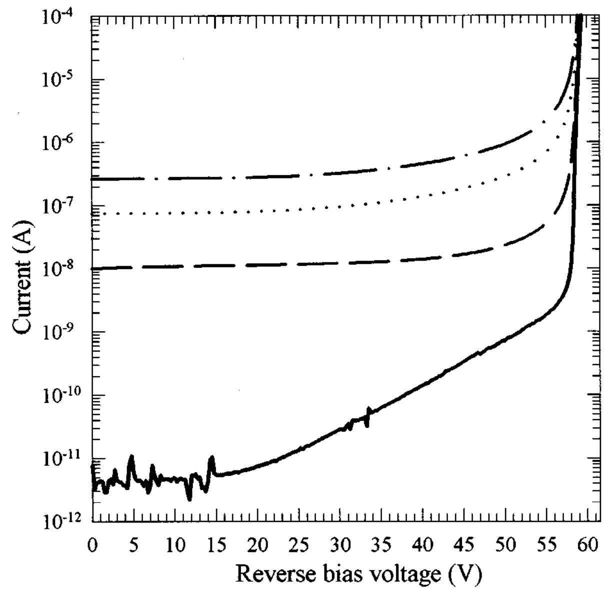

Fig. 1. Typical dark current characteristic (solid line) of APDs with a device area of 160×160 μm^2. The photo-response curves with 230 (dashed line), 297 (dot-dashed line), and 365 nm (dotted line) light are also shown.

Secondary ion mass spectroscopy and capacitance-voltage measurements indicate that the thin i region has a width w of 0.1 μm and an average p-type doping level of 1.5×10^{17} cm^{-3}. Doping levels in excess of 2×10^{18} cm^{-3} were deduced for the cladding layers adjacent to the i-region. Reverse dark current–voltage (IV) measurements indicate that the breakdowns are sharp and identical for all the diodes tested. The reverse dark current (shown in Fig. 1) is very low and increases by several orders of magnitude at the breakdown voltage $V_{\rm bd}$. The average dark current density at 95% $V_{\rm bd}$ is 8 μA/cm^2.

The spectral response of the APD structures was measured using a mercury–xenon lamp, a 0.22-m monochromator, and a lock-in amplifier. The output beam from the monochromator (~2 nm bandwidth), modulated with a mechanical chopper, was collimated and focussed onto the optical window of the APDs. To determine the spectral responsivity of the APDs, a commercial UV-enhanced Si photodiode was used to calibrate the optical system.

The multiplication characteristics of the APDs under different carrier injection conditions were investigated using UV light from the monochromator. DC photocurrents, from light

Manuscript received March 05, 2002; revised May 29, 2002. This work was supported in part by EPSRC (U.K.). The work of B. K. Ng was supported by Nanyang Technological University (Singapore) under a scholarship.

B. K. Ng, J. P. R. David, R. C. Tozer, and G. J. Rees are with the Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield S1 3JD U.K. (e-mail: bkng@ieee.org, j.p.david@sheffield.ac.uk).

F. Yan, C. Qin, and J. H. Zhao are with the Department of Electrical and Computer Engineering, Rutgers University, Piscataway, NJ 08540 USA.

Publisher Item Identifier 10.1109/LPT.2002.801112.

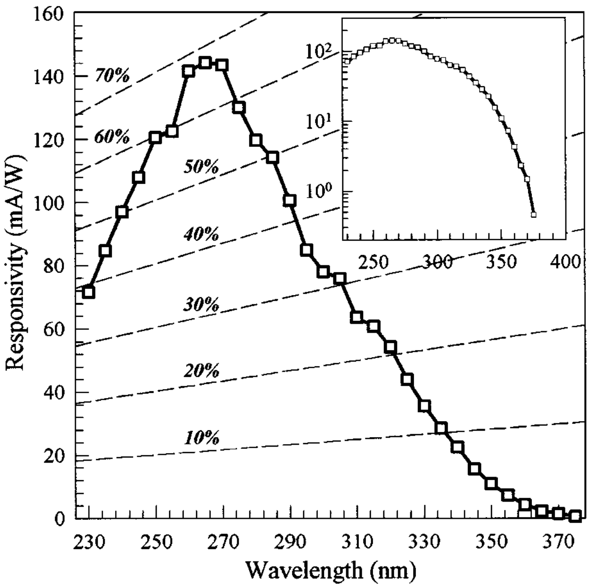

Fig. 2. Spectral responsivity of the APDs over the wavelength range of 230–375 nm at unity gain. The responsivity curves (dashed lines) corresponding to external quantum efficiency of 10% to 70% are also included for reference. The inset shows the same curve on a semi-logarithmic plot.

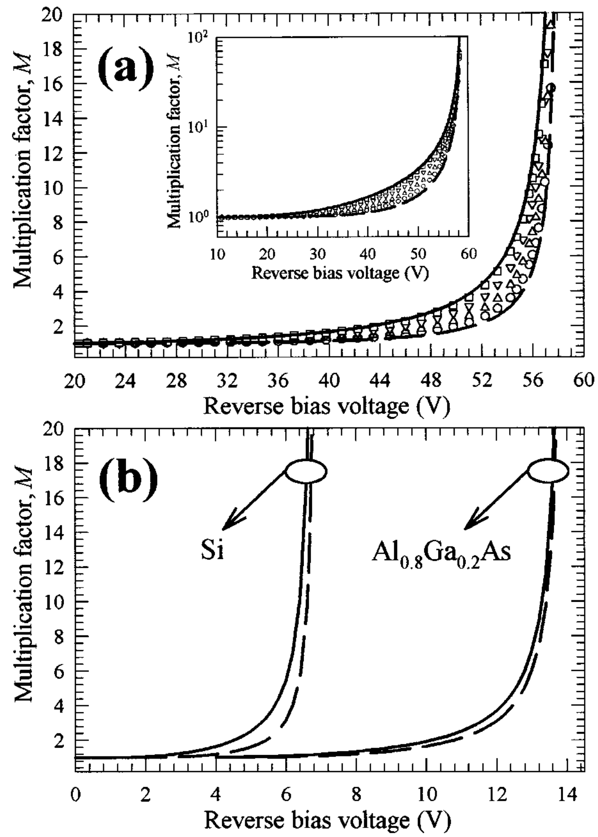

Fig. 3. Multiplication characteristics of the 4H–SiC APDs illuminated with 230- (dashed line), 240- (○), 250- (△), 265- (▽), 297- (□), and 365-nm (solid line) light are shown in (a). Inset shows the same results on a semilogarithmic plot to emphasize the large multiplication values. The electron (solid lines) and hole (dashed lines) initiated multiplication characteristics of Si and $Al_{0.8}Ga_{0.2}As$ diodes with $w = 0.1$ μm are depicted in (b) for comparison.

of wavelengths ranging from 230 to 365 nm, were measured as a function of reverse bias. AC measurements were also taken on some diodes using a lock-in amplifier with the UV light modulated at ~180 Hz. The multiplication characteristics from both dc and ac measurements were found to be identical. Gain uniformity of the layer was confirmed by identical multiplication characteristics measured on several diodes across the wafer. Multiplication values in excess of 200 were obtained.

The excess avalanche noise of the APDs at a center frequency of 10 MHz and a noise effective bandwidth of 4.2 MHz was measured using the method described previously by Li *et al.* [3]. Photogenerated carriers were injected into the high-field region of the APDs by focussing modulated 325-nm light from a HeCd laser to a small spot onto the optical access windows. Several diodes were measured to ensure reproducibility.

Fig. 2 shows the spectral responsivity of the APD at unity gain. A peak responsivity of ~144 mA/W at 265-nm wavelength, corresponding to an external quantum efficiency of about 67%, is achieved for the diodes. Although the unity gain spectral responsivity curves measured are similar to those of 6H-SiC diodes reported by Brown *et al.* [4], these 4H–SiC APDs do not exhibit photo-response for wavelengths longer than ~380 nm (see inset of Fig. 2) because of their wider bandgap. Consequently, 4H–SiC APDs are expected to have a better visible–blind performance than their 6H counterpart.

The photocurrent characteristics of the APDs illuminated with 230-, 297-, and 365-nm light are depicted, together with the dark current characteristic, in Fig. 1. The photocurrents obtained with 230–365-nm light are 1–3 orders of magnitude larger than the dark current. Fig. 3(a) shows the normalized multiplication characteristics of the APDs illuminated with 230–365-nm light. A small increase in the primary photocurrent ($<3\%$) with reverse bias is attributed to widening of the depletion region and a linear correction was used to obtain the normalized multiplication characteristics. The multiplication characteristics from longer wavelength light are consistently higher than those from light of shorter wavelengths. By extrapolating the multiplication characteristics, a value of 58.3 V was estimated for $V_{\rm bd}$, in close agreement with that obtained from reverse dark IV measurements.

Si [5] and $Al_{0.8}Ga_{0.2}As$ [6] are two materials that are also known to exhibit widely disparate ionization coefficients. For comparison, the electron and hole initiated multiplication characteristics of Si and $Al_{0.8}Ga_{0.2}As$ diodes with $w = 0.1$ μm are shown in Fig. 3(b). The results for the Si diode are simulated using the data from Tan *et al.* [5], while those of $Al_{0.8}Ga_{0.2}As$ are taken from [6]. Owing to the smaller bandgap in these materials, multiplication occurs at much lower voltages.

Since the absorption coefficient of 4H–SiC at a wavelength of 365 nm is approximately 80 cm^{-1} [7], this light is only weakly absorbed and carriers are uniformly created in the cladding layers and the high-field region of the diodes. Therefore, avalanche multiplication in the APDs illuminated by 365-nm light is initiated by a mixture of carriers comprising electrons injected from the thin p-cladding layer, electron–hole pairs created in the high-field region, and holes injected from the n-cladding layer. As the illumination wavelength decreases, the UV light is absorbed closer to the surface, and consequently

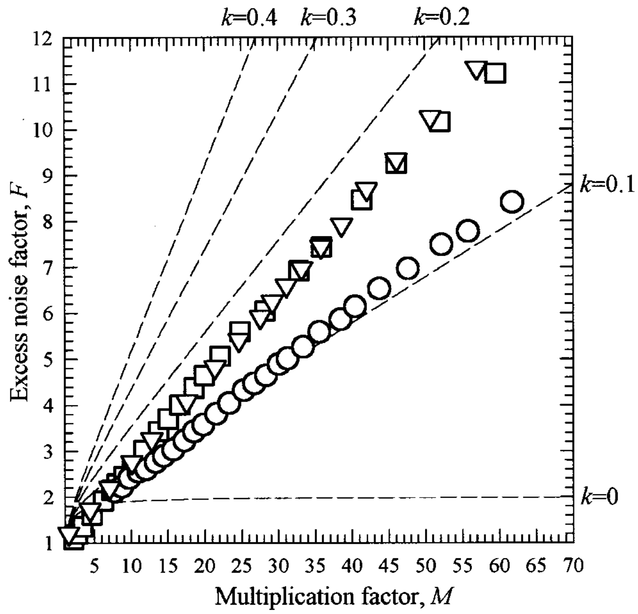

Fig. 4. Excess noise factor (F) versus multiplication factor (M) of the 4H–SiC APD (◯) obtained using 325-nm UV light. The excess noise from electron injection in Si (∇) and $Al_{0.8}Ga_{0.2}As$ (□) diodes with $w = 0.1$ μm are also shown. Dashed lines are predictions from McIntyre's local model for $k = 0$ to 0.4 in steps of 0.1.

fewer holes from the n-cladding layer are injected into the high field region. At a wavelength of 230 nm, we estimate that more than 95% of the light is absorbed in the top p^+ and p-cladding layers. Hence, the multiplication characteristic at 230 nm is mainly initiated by electron injection.

The higher multiplication characteristic measured with longer wavelength UV light shows unambiguously, for the first time, that $\beta > \alpha$ in 4H–SiC, where α and β are the electron and hole ionization coefficients, respectively. Despite the thin avalanche width in these 4H–SiC APDs there are still appreciable differences between the multiplication characteristics resulting from 230- and 365-nm light. This contrasts with the much closer electron- and hole-initiated multiplication characteristics of Si and $Al_{0.8}Ga_{0.2}As$ diodes with identical avalanche widths [see Fig. 3(b)]. By assuming that the multiplication characteristics of the 4H–SiC APDs from 365- and 230-nm light are due to hole- and electron-injection, respectively, the values of α and β are calculated using the local model and taking into account the nonuniform electric field profile in a manner similar to our other work [6]. The resulting β/α ratio is found to vary from about 20 to 2.5 over the measured electric field range. The actual β/α ratio would be higher than those estimated here since the multiplication characteristics from hole injection would be in reality higher than those from 365-nm light.

Fig. 4 shows the excess noise characteristics resulting from carriers injected using 325-nm light. The excess noise from electron initiated multiplication of Si and $Al_{0.8}Ga_{0.2}As$ diodes with $w = 0.1$ μm, simulated as before and taken from [8], respectively, are also included in the figure for comparison. The excess noise of the 4H–SiC APDs was measured up to a large multiplication factor in excess of 65 and was only limited by the dynamic range of the measurement system, thus demonstrating the high quality of these devices and the stability of their avalanche multiplication. The excess noise predicted by McIntyre's local model [9] for various k values (where $k = \alpha/\beta$ for multiplication initiated by holes) are also plotted in Fig. 4 for comparison. The excess noise of the 4H–SiC APDs corresponds to a k value of 0.1 in McIntyre's model. This is the lowest excess noise reported in a $w = 0.1$ μm structure to date.

The low excess noise achieved in the 4H–SiC APDs can be attributed, at least in part, to the large β/α ratio observed in these diodes. However, dead space, the distance a carrier must travel before it gains sufficient energy to impact ionize, may also contribute to the low excess noise, since it is known to become significant in thin structures [3]. The effect of dead space is clearly demonstrated by the similarly low excess noise achieved in thin Si and $Al_{0.8}Ga_{0.2}As$ diodes (Fig. 4) despite the smaller α/β ratio in these diodes. It should, however, be noted that the excess noise measured in the 4H–SiC APDs with 325-nm light is due to mixed carrier injection and would reduce further if only holes were injected into the high-field region to initiate the avalanche multiplication.

In conclusion, the multiplication results show unambiguously that $\beta > \alpha$ in 4H–SiC and that the β/α ratio remains large even in thin 4H–SiC APDs. Low excess noise corresponding to $k = 0.1$ in the local noise model was measured using 325-nm light. We expect even thinner 4H–SiC structures to give, in addition to a lower operating voltages, further reductions in excess noise by virtue of the increased dead space effects.

REFERENCES

[1] A. O. Konstantinov, Q. Wahab, N. Nordell, and U. Lindefelt, "Ionization rates and critical fields in 4H silicon carbide," *Appl. Phys. Lett.*, vol. 71, no. 1, pp. 90–92, July 1997.

[2] F. Yan, C. Qin, J. H. Zhao, and M. Weiner, "A novel technology for the formation of a very small bevel angel for edge termination," *Electron. Lett.*, submitted for publication.

[3] K. F. Li, D. S. Ong, J. P. R. David, G. J. Rees, R. C. Tozer, P. N. Robson, and R. Grey, "Avalanche multiplication noise characteristics in thin GaAs p^+–i–n^+ diodes," *IEEE Trans. Electron Devices*, vol. 45, pp. 2102–2107, Oct. 1998.

[4] D. M. Brown, E. T. Downey, M. Ghezzo, J. W. Kretchmer, R. J. Saia, Y. S. Liu, J. A. Edmond, G. Gati, J. M. Pimbley, and W. E. Schneider, "Silicon carbide UV photodiodes," *IEEE Trans. Electron Devices*, vol. 40, pp. 325–333, Feb. 1993.

[5] C. H. Tan, J. C. Clark, J. P. R. David, G. J. Rees, S. A. Plimmer, R. C. Tozer, D. C. Herbert, D. J. Robbins, W. Y. Leong, and J. Newey, "Avalanche noise measurement in thin Si p^+–i–n^+ diodes," *Appl. Phys. Lett.*, vol. 76, no. 26, pp. 3926–3928, Jun. 2000.

[6] B. K. Ng, J. P. R. David, S. A. Plimmer, G. J. Rees, R. C. Tozer, M. Hopkinson, and G. Hill, "Avalanche multiplication characteristics of $Al_{0.8}Ga_{0.2}As$ diodes," *IEEE Trans. Electron Devices*, vol. 48, pp. 2198–2204, Oct. 2001.

[7] S. G. Sridhara, R. P. Devaty, and W. J. Choyke, "Absorption coefficient of 4H silicon carbide from 3900 to 3250 Å," *J. Appl. Phys.*, vol. 84, no. 5, pp. 2963–2964, Sept. 1998.

[8] B. K. Ng, J. P. R. David, R. C. Tozer, M. Hopkinson, G. Hill, and G. J. Rees, "Excess noise characteristics of $Al_{0.8}Ga_{0.2}As$ avalanche photodiodes," *IEEE Photon. Technol. Lett.*, vol. 14, pp. 522–524, Apr. 2002.

[9] R. J. McIntyre, "Multiplication noise in uniform avalanche diodes," *IEEE Trans. Electron Devices*, vol. ED-13, pp. 164–168, 1964.