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Avalanche Multiplication and Breakdown in 4H-SiC Diodes

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Abstract. The measured photomultiplication and excess noise characteristics of two 4H-SiC p-i-n diodes, with *i*-region widths of 0.105 μm and 0.285 μm, were modelled using a nonlocal multiplication model to determine the ionization threshold energies and the impact ionization coefficients of 4H-SiC. The modelled ionization coefficients accurately predicted the breakdown voltage of a 0.485 μm p-i-n structure. The breakdown voltage of 4H-SiC calculated using these parameters is approximately 7.2 and 4.6 times higher than that of similar Si and $Al_{0.8}Ga_{0.2}As$ structures respectively. Dead space, the minimum distance required for carriers to equilibrate in the electric field, has to be taken into account to accurately predict the breakdown voltage in thin devices.

Introduction

4H-SiC is a potential candidate for high power and high frequency applications owing to its wide band gap (3.25eV) and high saturated drift velocity. The design of high temperature, high power and high frequency devices using this material requires an accurate knowledge of its impact ionization characteristics. The impact ionization coefficients in 4H-SiC reported by Konstantinov *et al.* [1] were obtained from experimental results using a local assumption. While the use of a local model may be appropriate for thick bulk structures, several studies [2, 3] have shown that this assumption is no longer valid for thin devices where dead space, the minimum distance required for carriers to equilibrate in the electric field, represents a significant fraction of device widths.

In this paper, we report the avalanche multiplication and breakdown characteristics in thin 4H-SiC diodes. Diodes with sub-micron avalanching widths were used in this study to investigate the effect of dead space on the avalanche characteristic of 4H-SiC. The impact ionization coefficients and impact ionization threshold energies, obtained from modeling the multiplication and excess noise characteristics using a nonlocal model, were used to evaluate the breakdown voltage of 4H-SiC as a function of device width. The breakdown voltages of Si and $Al_{0.8}Ga_{0.2}As$ were also calculated for comparison.

Experiment and Modelling

Three 4H-SiC p-i-n structures were used for this work. Two of the layers were reported in our earlier work [4] and have i-region widths, *w*, of 0.105 μm and 0.285 μm. The third layer comprises a nominal i-region width of 0.5 μm capped with a 0.2 μm p^+ layer. Square mesa diodes with areas ranging from 60 x 60 μm^2 to 540 x 540 μm^2 were fabricated and windows were formed on the top

ohmic contacts to provide optical access. Secondary ion mass spectroscopy (SIMS) measurement carried out on the thickest p-i-n structure gave an i-region width of 0.485 μm, as shown in Fig. 1.

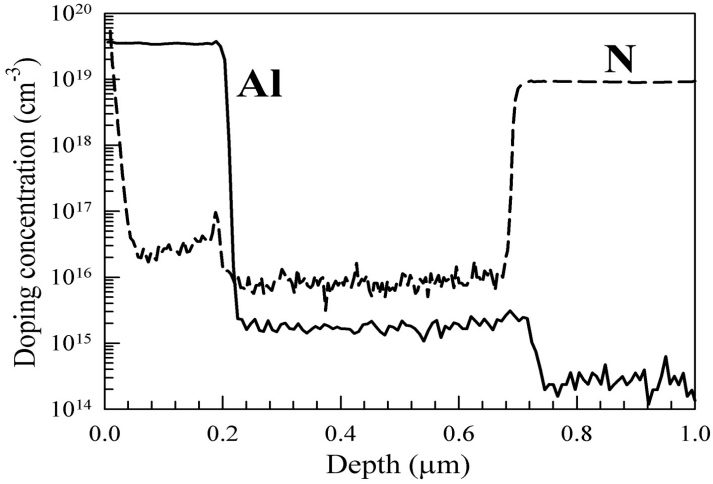

Fig. 1. SIMS profile of the nominally 0.5 μm 4H-SiC p-i-n diode. The p-type (solid line) and n-type (dashed line) dopants are Al and N respectively.

Photomultiplication and excess noise characteristics of p-i-n diodes with w = 0.105 μm and w = 0.285 μm were measured using 230 - 365 nm light from a mercury-xenon lamp [5]. Both structures exhibit very low dark currents prior to avalanche breakdown and the measured photocurrents are at least an order of magnitude larger than the dark current. Both DC and AC measurements were performed to ensure reproducibility. The breakdown voltage of the thicker 0.485 μm p-i-n structure was determined from its reverse dark current characteristic.

The experimental results from the diodes with w = 0.105 μm and w = 0.285 μm were modelled using the nonlocal model of Ong *et al.* [6], taking into account the distributed carrier injection arising from weakly absorbed UV light and the effect of non-uniform electric field in each structure. The breakdown voltage of 4H-SiC diodes as a function of device width was calculated with the nonlocal model using the fitted impact ionization coefficients and impact ionization threshold energies. For comparison, the impact ionization coefficients of Konstantinov *et al.* were used to compute the breakdown voltage of 4H-SiC diodes within the framework of the local model. In addition, the breakdown characteristics of Si and $Al_{0.8}Ga_{0.2}As$ diodes were also calculated using the nonlocal model, and the parameters reported by Tan *et al.* [7] and Ng *et al.* [8] respectively.

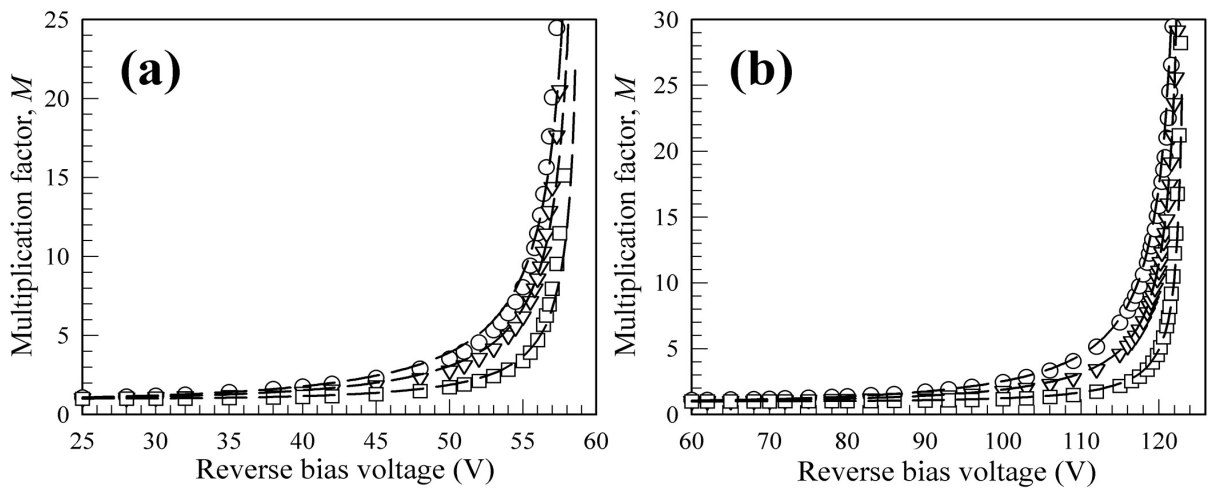

Fig. 2. Measured (symbols) and modeled (dashed lines) photomultiplication characteristics of the 4H-SiC diodes with a) w = 0.105 μm and b) w = 0.285 μm from 230 nm (□), 265 nm (▽) and 365 nm (○) wavelength excitation.

Results and Discussions

The photomultiplication and excess noise characteristics of the 0.105 μm and 0.285 μm p-i-n diodes from different excitation wavelengths are shown in Fig. 2 and 3 respectively. It is clear from Fig. 2 that the measured multiplication characteristics with longer wavelength light are always higher than those of shorter wavelengths in both structures. This shows unambiguously that the hole ionization coefficient is larger than that of electron in 4H-SiC since varying the illumination wavelength from 230 nm to 365 nm changes the initiating carriers from pure electrons to mixed carriers. The higher excess noise measured with shorter wavelength light further corroborates the deduction from the multiplication measurement. As depicted in Fig. 2 and 3, the predictions from the nonlocal model are in good agreement with the experimental results using hole and electron ionization threshold energies of 8 eV and 12 eV respectively [5].

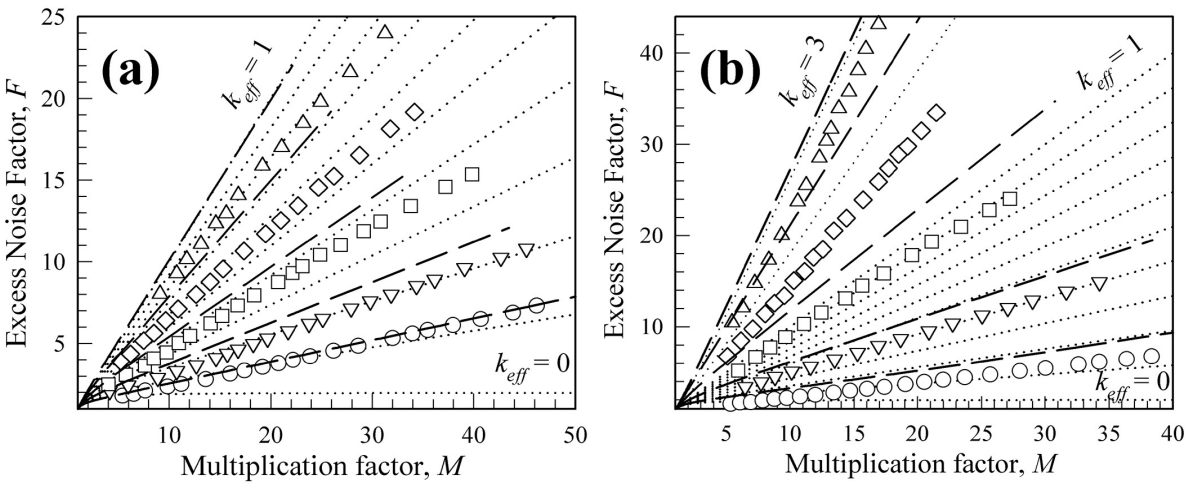

Fig. 3. Measured (symbols) and modeled (dashed lines) excess noise characteristics of the 4H-SiC diodes with a) w = 0.105 μm and b) w = 0.285 μm from 230 nm (△), 240 nm (◇), 250 nm (□), 265 nm (▽) and 365 nm (○) wavelength excitation. Dotted lines are McIntyre's local prediction [9] for k_{eff} = 0 to 1 in steps of 0.1 and k_{eff} = 2, 3.

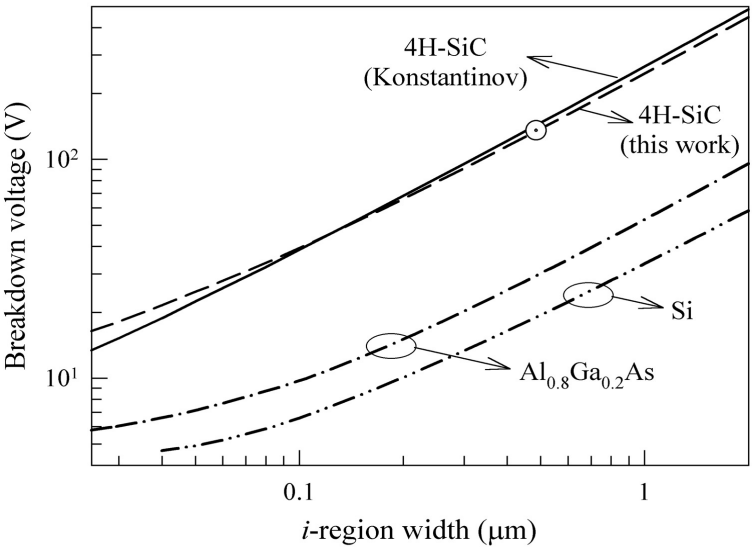

Fig. 4. Calculated breakdown voltage of ideal p-i-n diodes for 4H-SiC, Si and $Al_{0.8}Ga_{0.2}As$ plotted as a function of the i-region widths. The measured value of a 4H-SiC p-i-n diode with i-region width of 0.485 μm (⊙) is also shown for comparison.

Figure 4 shows the breakdown voltage of 4H-SiC diodes calculated using the nonlocal model and the modelled parameters. The prediction is found to be in agreement with the measured breakdown voltage of the 0.485 μm p-i-n structure. By contrast, breakdown voltages calculated using the ionization coefficients of Konstantinov *et al.* are slightly higher in bulk structure but are lower by up

to ~20% for thin diodes. In addition, the multiplication characteristics of thin diodes at low multiplication values predicted by the local model were found to differ significantly from those of the nonlocal model used in this work. These differences are in agreement with the work of Plimmer *et al.* [10], in which it was found that the local model underestimated the breakdown voltage as device width is reduced and the low multiplication values calculated for thin structures are highly sensitive to the dead space effect. The discrepancy in predicting the breakdown voltages and multiplication characteristics of thin diodes is attributed to the consideration of dead space effect in our analysis. As shown in Fig. 4, the breakdown voltage of 4H-SiC diode is approximately 7.2 and 4.6 times higher than that of similar Si and $Al_{0.8}Ga_{0.2}As$ structures respectively. These results indicate that 4H-SiC is well suited for high power applications.

Conclusion

The impact ionization threshold energies and the ionization coefficients of 4H-SiC were determined by modelling the measured multiplication and excess noise characteristics of short 4H-SiC p-i-n diodes under different carrier injection conditions. The electron ionization threshold energy was found to be larger than that of holes in 4H-SiC. The breakdown voltage of 4H-SiC calculated using these parameters is approximately 7.2 and 4.6 times higher than that of similar Si and $Al_{0.8}Ga_{0.2}As$ structures respectively. The nonlocal dead space effect has to be taken into account to accurately predict the breakdown voltage in thin devices. The results indicate that 4H-SiC is well suited for high power applications.

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