4H-SiC UV Photo Detectors With Large Area and Very High Specific Detectivity

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***Abstract*—Pt/4H-SiC Schottky photodiodes have been fabricated with the device areas up to 1 cm^2. The I–V characteristics and photoresponse spectra have been measured and analyzed. For a 5 mm × 5 mm area device leakage current lower than 10^{-15} A at zero bias and 1.2 $\times 10^{-14}$ A at -1 V have been established. The quantum efficiency is over 30% from 240 to 320 nm. The specific detectivity, D^*, has been calculated from the directly measured leakage current and quantum efficiency are shown to be higher than 10^{15} cmHz$^{1/2}$/W from 210 to 350 nm with a peak D^* of 3.6 $\times 10^{15}$ cmHz$^{1/2}$/W at 300 nm.**

***Index Terms*—Leakage current, photodiode, Schottky diodes, ultraviolet detectors.**

I. INTRODUCTION

THE sensitivity of a photodetector is primarily limited by the background radiation (e.g., the 300-K blackbody radiation of the earth) and the noise of the detector, which increases as the leakage current increases [1]. Since the 300-K blackbody radiation is mainly in the visible and infrared range, it limits the sensitivity of most photodetectors that have cutoffs in this range but barely affects those detectors with cutoffs in the UV range, i.e., the visible blind photodetectors. The solar radiation is practically zero on the earth in the solar blind UV range from 245 and 280 nm [2]. The photodetection in this range is not affected by the solar radiation and is practically solar blind. Therefore, if photodetectors can be fabricated with high quantum efficiency, low leakage current, and visible blindness or even solar blindness, photodetection with very high sensitivity can be achieved even under solar irradiation background. In practice, high sensitivity visible blind or solar blind UV detectors are highly sought after for astronomical and terrestrial applications.

In the past decade, tremendous progress has been made in the material growth and processing of wide bandgap semiconductors, particularly SiC and GaN, and high quality SiC and GaN wafers are now commercially available [3], [4]. Both types of semiconductors have very wide bandgap (4H–SiC = 3.2 eV and GaN = 3.4 eV) and are visible blind. Due to the wide bandgap of SiC and GaN, the leakage current can be many orders of magnitude lower than the leakage current of Si detectors, making SiC and GaN good candidates for high sensitivity visible blind UV detection.

GaN has the advantages of the availability of heterostructures, which allows to design cutoff wavelength in the UV range by using AlGaN with different Al percentage. It therefore adds great flexibility in detector design and relieves or elminates the requirement of optical filters. SiC, however, has much better material maturity. For example, the defect density of SiC, $10 \sim 10^3/\mathrm{cm}^3$ [5], is many orders of magnitude lower than that of GaN, $10^6 \sim 10^{10}/\mathrm{cm}^3$ [4]. Additionally, SiC substrate and epi-growth technologies have developed to such a level as to allow the fabrication of many different types of SiC photodetectors with desired features. Moreover, 4H-SiC has very high breakdown field, outstanding radiation hardness, excellent chemical and mechanical rigidity, good thermal conductivity and as such are excellent candidates for photo detection in high temperature and high radiation environment conditions [3], [6]. SiC UV p-i-n photodiodes have already been fabricated [7] and are commercially available. SiC avalanche photodiodes with extremely high gain (10^7) and low excess noise have also been demonstrated [8], [9]. In this paper we report on the fabrication of 4H-SiC Schottky photodiodes with large areas (up to 1 cm × 1 cm) which show extremely low leakage current and excellent detectivity in the UV range.

II. DEVICE FABRICATION

4H-SiC Schottky photodiodes are fabricated on 2-in production-grade 4H-SiC wafers purchased from Cree Inc., which have n$^-$ epilayer grown on n$^+$ substrate. The wafers were first oxidized in wet oxygen at 1050 °C for 3 h. Another 200 nm PECVD SiO$_2$ and 300 nm PECVD Si$_3$N$_4$ were then deposited on the top of the n$^-$ side as the passivation layer. After oxide removal from the backside of the wafer, Ni was deposited on the n$^+$ side for n-type ohmic contact. The n-type ohmic contact was formed by annealing samples at 1050 °C for 10 min in the N$_2$ forming gas with 3.5% H$_2$. After oxide etching, 75 Å semi-transparent Pt was deposited on n$^-$ side to form Schottky contact. A gold contact ring for wire bonding was then deposited on the top of the semi-transparent Pt. The width of the contact ring is 100 μm. 4H-SiC Schottky diodes of four different sizes have been fabricated and the areas are 0.25 mm × 0.50 mm, 2 mm × 2 mm,

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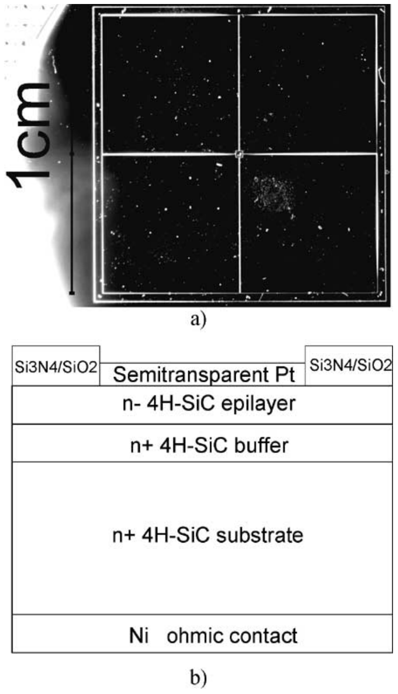

Fig. 1. (a) Top view of a 1 cm × 1 cm Pt/4H-SiC Schottky photodiode. (b) Cross-sectional view of Pt/4H-SiC Schottky photodiodes.

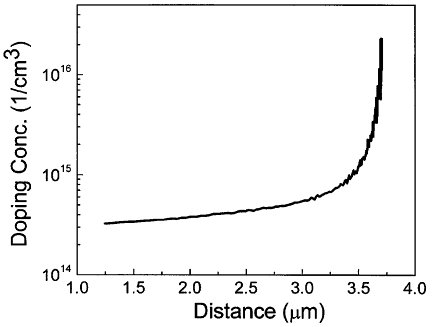

Fig. 2. Doping profile of 4H-SiC wafers determined from C–V measurement at 100 kHz.

5 mm × 5 mm, and 1 cm × 1 cm, respectively. Fig. 1(a) and (b) shows the top view and the cross sectional view of the 4H-SiC Schottky photodiodes fabricated.

III. RESULTS

A. Doping Profile

C–V measurements were taken by Keithley 590 C–V analyzer to determine the doping profile. The measurement was carried out at 100 kHz. Fig. 2 shows the corresponding doping profile determined from $d(1/C^2)/dV$. As shown in Fig. 2, the thickness of the n$^-$ layer is about 3.7 μm and the doping concentration varies from $3\times10^{14}/\text{cm}^3$ at the surface to $3\times10^{15}/\text{cm}^3$ at the interface between n$^-$ epi-layer and substrate.

B. I–V Measurement

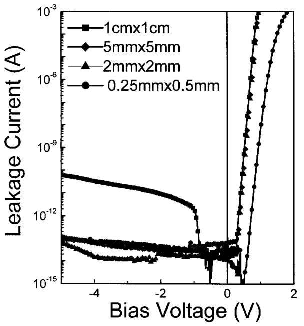

Fig. 3. Typical I–V characteristics of Pt/4H-SiC Schottky photodiodes of different sizes from 0.25 mm × 0.5 mm to 1 cm × 1 cm.

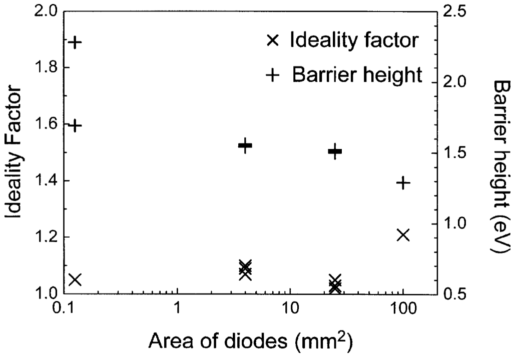

Fig. 4. Barrier heights and ideality factors of Pt/4H-SiC Schottky photodiodes of different sizes determined from their forward I–V characteristics.

I–V characteristics of Pt/SiC Schottky diodes are measured by Keithley 4200 semiconductor characterization system at room temperature in the dark. Fig. 3 shows the typical I–V characteristics of diodes of different sizes. The forward current of semi-log I–V shows excellent linearity across nine orders of magnitude. For metal/semiconductor Schottky diodes, the current can be expressed by [10]

$$I = A\cdot A^*\cdot T^2\cdot\exp\left(-\frac{q\Phi_b}{nk_BT}\right)\cdot\left[\exp\left(\frac{qV}{nk_BT}\right)-1\right] \quad (1)$$

according to the thermoionic emission theory, where A is the area of the diode, A^* is Richardson's constant, Φ_b is the barrier height, n is the ideality factor, k_B is Boltzmann's constant, q is the electron charge, and T is the absolute temperature. Using the theoretical Richardson's constant, 146 A/W [11], the ideality factor and the Schottky barrier height were determined by fitting the linear region of the forward I–V curves.

Fig. 4 summarizes the ideality factor and barrier height of diodes of different sizes. The ideality factor is around 1.05 for all other diodes except for the 1 cm × 1 cm diode, which showed an ideality factor of 1.20. The average barrier height of the 5 mm × 5 mm diodes determined from I–V characteristics is 1.52 eV.

According to the relationship given by Itoh *et al.* [11], the barrier height of 4H-SiC Schottky contact can be expressed by

$$\Phi_b = 0.70\cdot\Phi_m - 1.95 \quad (2)$$

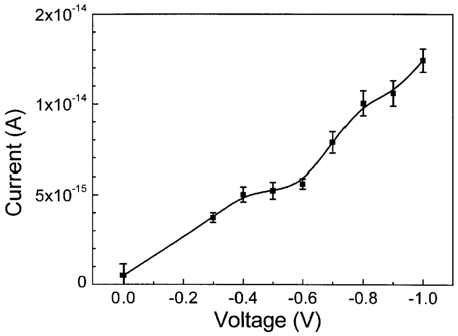

Fig. 5. Reverse I–V characteristics of a 5 mm × 5 mm Pt/4H-SiC Schottky photodiode.

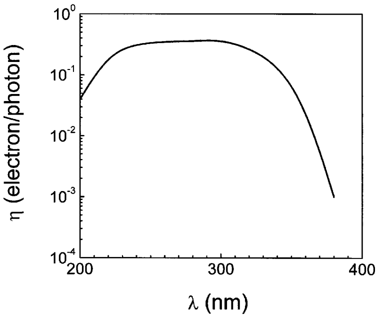

Fig. 6. Typical photo response spectra in quantum efficiency of Pt/4H-SiC Schottky photodiodes.

where Φ_m is the work function of the Schottky metal. By using the 5.65 eV work function of Pt, the barrier height of Pt/4H-SiC Schottky junction is 2.0 eV, which is substantially higher than the barrier height determined from I–V measurement results. The difference is still under investigation and is partially attributed to the inhomogeneous barrier height effect [12], [13]. It is also noted that the barrier height decreases as the area of the photodiode increases. Therefore, macro-defects, such as micropipes and polytype inclusions (density $<$10 cm ^{2}), are likely to be responsible for the lowering of barrier height, too.

As shown in Fig. 3, the leakage current is around 10^{-13} A between 0 and 1 V for all diodes. The leakage current of all diodes except for the 1 cm × 1 cm one remains well below 10^{-12} A up to -5 V. The results are very reproducible from batch to batch. Three 5 mm × 5 mm, three 2 mm × 2 mm, and one 1 cm × 1 cm diodes have been fabricated in four different batches. All of them showed very consistent results. The measured leakage current does not show any area dependence and seems limited by the system noise. In order to determine the actual leakage current, one 5 mm × 5 mm diode was tested with calibrated equipment at the laboratories of Keithley Instruments Inc.

The leakage current was measured with a 4200-SCS and pre-amplifier remotely mounted on to probe station to minimize any cable leakage. The measurement was carried out in a light–proof Cascade Summit 12000 Probe Station. The instrument specification at 1-pA range is 10 fA +/- 1% reading accuracy, and 100-pA resolution. The typical current measurement noise (peak to peak) is 0.2% measurement range. At 1-pA range, the corresponding noise is 2 fA. An offset current measurement is performed with probes up and the offset current, which is 4 fA, is subtracted from subsequent measurements. By using this technique, more accurate measurement can be made below the offset specification of the instrument. Since the capacitance of the diode is relatively large ($\sim$5 nF), the measured current is the combination of leakage current and the displacement current due to voltage ramp. The settling of the displacement current depends on the capacitive load of device under test (DUT) and input impedance of the instrument at specific range. In this case, the capacitance is fairly large and the current range used is very small (1-pA range), which results in very long settling time. The error bar on measurement is characterized by standard deviation of 100 readings. The resulted noise is close to the noise specification of the instrument (2-fA peak-to-peak typical). Fig. 5 shows the leakage current measured between 0 and -1 V with the settling time long enough to make the displacement current negligible. The leakage current is lower than 1 fA at 0 V, which is under the noise floor of the measurement instrument. Therefore, the measured leakage current is from the test system at 0 V. At -1 V, the leakage current is 12 fA. The corresponding leakage current density is $<$4 fA/cm^2 at 0 V and 50 $\mathrm{fA/cm^2}$ at -1 V. Note that the leakage current density of Pt/SiC Schottky diodes at room temperature is now comparable to the leakage current of photocathodes [14]. The dynamic resistance, R_o, at 0 V is determined from $(dV/dI)_{V=0}$ to be 1 ×10^{14} Ω for the 5 mm × 5 mm diode. The corresponding R_oA is 2.5 ×10^{13} $\Omega \cdot \mathrm{cm}^2$.

Note that the leakage current at zero bias is many orders of magnitude higher than the saturation current determined from forward I–V curves, which is typically around 10^{-20} A for 5 mm × 5 mm diodes. The difference suggests that the saturation current at low bias voltage is unlikely to be the dominating factor and does not present the real leakage current of the SiC photodiodes.

C. Photoresponse Measurement

The quantum efficiency of the SiC Schottky photodiodes has been determined based on the photoresponse spectra between 200 nm and 400 nm, which is shown in Fig. 6. Unlike GaN, 4H-SiC is indirect semiconductor, and does not have a sharp cutoff edge at the band edge. The absorption coefficient increases slowly from 385 nm as the wavelength decreases. As a result, the quantum efficiency of 4H-SiC Shcottky diodes increases gradually from less than 0.1% at 380 nm to 37% at 300 nm. The maximum quantum efficiency is around 37% and nearly constant from 240 to 300 nm. The absorption coefficient of Pt at 300 nm is 9.2 ×10^5 [15] and the semitransparent 75-ÅPt will absorb 50% of the photons at 300 nm. Therefore, the internal quantum efficiency is about 80% even without including the reflection loss. At wavelengths shorter than 240 nm, the quantum efficiency decreases as the wavelength decreases. This decrease is most likely due to the influence of the surface recombination, which becomes significant when the penetration depth starts to be comparable with the dead zone caused by the surface recombination.

The uniformity of the quantum efficiency has also been checked across a 5 mm × 5 mm device. The fluctuation of the quantum efficiency is 9% across the device. The average quantum efficiency in the center is about the same as the quantum efficiency at the edge, indicating that the photogenerated carriers can be efficiently collected by the 75-Å Pt thin film.

For a detector at zero bias, the noise of the detector is dominated by the Johnson noise. D^* is one of the most frequently used figure of merits to evaluate the sensitivity of photodetectors and is defined as [16]

$$D^* = \frac{q\eta}{h\nu} \cdot \left[\frac{R_o A}{4k_B T}\right]^{1/2} \tag{3}$$

when the Johnson noise dominates, where η is the quantum efficiency, h is the Planck constant, ν is the radiation frequency, R_o is the dynamic resistance at zero bias, and A is the detector area. The D^* of 4H-SiC Schottky photodiodes is calculated based on the directly measured results of our 5 mm × 5 mm photodiodes and compared with other common photo detectors in Fig. 7. The maximum D^* of 4H-SiC Schottky is $3.6 \times 10^{15}\text{cmHz}^{1/2}/\text{W}$ at 300 nm and the D^* is above $10^{15}\text{cmHz}^{1/2}/\text{W}$ from 210 to 350 nm. The D^* is two orders of magnitude higher than the D^* of Si photodiodes and three orders of magnitude higher than the D^* of Si CCD [14], [17]. As expected, the D^* of SiC photodiodes is not limited by the 300-K background limit, namely the D^* of background limited infrared photodiodes (BLIP), as most infrared detectors.

The D^* of GaN detectors is also calculated based on the results of a 5 mm × 5 mm GaN Schottky photodiode fabricated in Goddard Space Flight Center [18], which shows a leakage current density of 5.6×10^{-11} A/cm^2 at $-$ 0.5 V and R_o of 1.1×10^{11} Ω. As shown in Fig. 7, the D^* of SiC detectors is about two orders of magnitude higher than the D^* of GaN detectors. It is noted that $D*$ of GaN detectors reported by other groups has been calculated from R_o derived from the extrapolated saturation current giving an over optimistic value of D^*. In this paper, the D^* of GaN photodiodes is calculated from the directly measured leakage current and responsivity. The leakage current density of the GaN photodiode is comparable with the best results from small GaN diodes [19], [20] and the D^* shown in Fig. 7 should represent the state-of-the-art D^* of GaN photodiodes.

The D^* of SiC Schottky photodiodes is still about one order of magnitude lower than S20 PMT. It should be noted that the current results are achieved on SiC wafers containing many types of surface defects [5], which will cause inhomogeneous barrier height across the devices. As a result, the effective barrier height is substantially lower than the ideal value, 2.0 eV for Pt/4H-SiC. As the SiC crystal quality improves, giving rise to low surface defects density, the barrier height can be substantially increased and the leakage current can be further reduced even for large area photodiodes. Moreover, the quantum efficiency can be further improved by reducing the thickness of the semitransparent metal. Therefore, it should be possible to fabricate SiC photodiodes with D^* higher than or at least comparable to most PMTs.

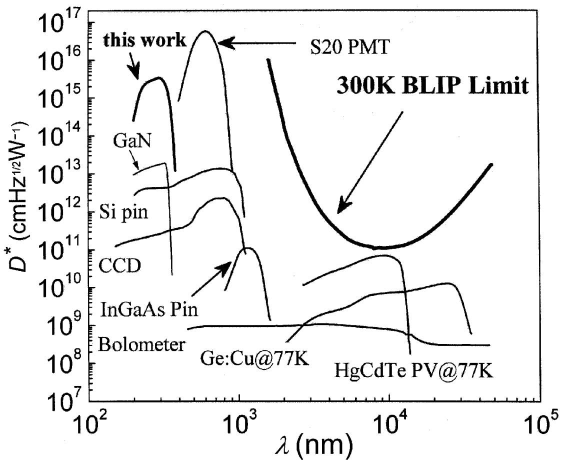

Fig. 7. Comparison between SiC Schottky 5 mm × 5 mm photodiodes made in this work and some common detectors [14], [17]. The D^* of GaN detectors is from our GaN 5 mm × 5 mm Schottky photodiodes with a leakage current of 1.6×10^{-12} A at 0 V. The 300-K blackbody radiation limited D^*, 300 K BLIP limit, is also inset as a reference.

It should also be pointed out that the demonstrated SiC photodiodes show good quantum efficiency across the solar blind UV, 245 to 280 nm even though the top Pt film absorb 50% of incident photons. For small area detectors which do not require continuous Pt film to collect the photon generated holes, quantum efficiency higher than 80% can be easily achieved in solar blind UV. As pointed out, solar blind filters with a cutoff rate of 10 dB/nm from 285 to 300 nm is required in solar blind UV detection [2], [21]. Solar blind detection may be practically unachievable for semiconductor detectors without special filters. Therefore, SiC photodiodes with very high D^*, although not intrinsically solar blind, can be a very good candidates for solar-blind UV detection when employed with proper solar-blind filters.

IV. Conclusion

Pt/4H-SiC Schottky photodiodes with the device area of 0.25 mm × 0.50 mm, 2 mm × 2 mm,5 mm × 5 mm, and 1 cm × 1 cm have been fabricated and characterized. The I–V measurement results show that the ideality factor is less than 1.05 for diodes up to 5 mm × 5 mm. The photodiodes showed extremely low leakage current. The leakage current of a 5 mm × 5 mm device is less than 1×10^{-15} A at zero bias and 1.2×10^{-14} A at -1 V. The photoresponse results show that the quantum efficiency is over 30% and nearly flat from 320 to 240 nm. The D^* at zero bias has been calculated based on the directly measured dynamic resistance at zero bias. The peak of the D^* of 4H-SiC Schottky is found to be 3.6×10^{15} cm · Hz$^{1/2}$/W at 300 nm and the D^* is above 10^{15} cm · Hz$^{1/2}$/W from 210 to 350 nm.

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