Deposition of Crystal SiCN Thin Film on Si Substrate for High Gain Ultraviolet Detecting Applications

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Abstract

In this work, we report a novel n-SiCN/p-SiCN homojunction developed on Si substrate for low cost and high temperature ultraviolet detecting applications. The photo/dark current ratio of the junction under -5 volt bias, with and without irradiation of 254 nm UV light are 1940, and 121.1 at room temperature (25 ℃), and at 125 ℃, respectively. Compared to the reported UV detectors with 4H-SiC or β-SiC, the developed n-SiCN/p-SiCN homojunction has better photo/dark current ratio in both room and elevated temperature.

Keywords：homojunction; detector; ultraviolet (UV), SiCN, RTCVD.

1. Introduction

Ultraviolet photodetectors have many potential applications such as space communication, ozone layer monitoring, missile plume detection, flame detection, biological, and chemical applications [1]-[4], thus have drawn much attention in the recent years. In the past, major compact ultraviolet (UV) sensors are prepared with GaN, β-SiC on Si, 4H-SiC, diamond, and 6H-SiC. The GaN/6H-SiC or 6H-SiC UV sensor has better high temperature characteristics [5],[6], but is more expensive [7]-[10]. Even, the β-SiC on Si substrate is inexpensive and has been studied widely for its lower cost. Nevertheless, its photo/dark current ratio (PDCR) is low, especially in high temperature [11],[12]. Bedsides, devices with diamond have a lower dark current (~ pA) and very high operation temperature [13]-[15]; however, they still need expensive substrates to grow high quality diamond film. Hence, it is interesting to search a new material for low cost high temperature UV detecting applications. The wide band gap semiconductor, silicon carbon nitride (SiCN) has many interesting physical characteristics such as hardness, oxidation resistance, high thermal stability, and corrosion resistance [16],[17]. Especially, the cubic crystalline SiCN (c-SiCN) film deposited on p-Si(100) substrate by the rapid thermal chemical vapor deposition (RTCVD) has wide band gap of 3.2 ~ 4.4 eV [18],[19], which is lager than or comparable to 6H-SiC of 3.0 eV, β-SiC on Si of 2.2 eV, GaAs of 1.42 eV, and GaN of 3.36 eV [7]. Furthermore, the epitaxial SiCN on Si substrate offers the advantages of economic Si material and very large scale integrated (VLSI) compatible processing thus lowering the cost to enhance the applications, and adopted in this work.

In this article, we were considered the n-SiCN/p-SiCN homojunction in detail for the application. The PDCR of the junction under 254 nm wavelength light source at various operating temperatures were measured and compared. Results show under -5 volt bias, the homojunction has the PDCR of 1940, and 121.1 at room temperature, and 125 ℃, respectively. Thus is preferable for low cost and high temperature UV detecting applications.

2. Experiments

The samples with junction area of 0.5 × 0.5 cm^2 and schematic diagram showed in Fig. 1. The junction prepared on the p-type Si(100) substrate with resistivity of 4-10 Ω-cm by a RTCVD system. After cleaning the Si substrate was sent to chamber, then rapidly raised the substrate temperature to 1150 ℃ and held for 12.5 minutes to deposit the 5000 Å thick p-SiCN film with growth rate of 400 Å/min (2.0 mTorr). Then deposited a 5000Å n-SiCN layer on the top of p-SiCN layer by the same process except, the PH_3 was used to replace the B_2H_6 as doping gas. The typical concentration of the phosphorus doped layers is ~ 1×10^{19} cm^{-3}, and it is ~ 1×10^{18} cm^{-3} for boron doped layers [16]. Sequentially, Ni (1500 Å) metal was evaporated on the n-SiCN and p-SiCN surfaces for top finger electrodes. A more detailed description for growing c-SiCN and subsequent material characterizations can be found in elsewhere [7], [16]. Finally, the samples were annealed at 450 ℃ under nitrogen ambient for 15 minutes to form the ohmic contact [7]. The flow rates of SiH_4 (reaction gas), C_3H_8 (carbon source), NH_3 (reaction gas), PH_3 (doping gas), B_2H_6 (doping gas), are 80 sccm, 80 sccm, 80 sccm, 10 sccm, 12 sccm, respectively.

3. Results and discussion

The composition of the RTCVD prepared c-SiCN alloy is dependent on the carbon source used [16]. In this work, C_3H_8 was used as the carbon source, and has the composition of $Si_{0.48}C_{0.15}N_{0.37}$ [16] measured with auger electron spectroscopy (AES, VG. Microlab 310D). The crystalline structure of the c-SiCN film was examined by transmission electron diffraction (TEM, Hitachi HF-2000) and X-ray diffraction (XRD, Rigaku D/MAX 2500), while the morphology by scanning electron microscopy (SEM, Philips XL-40FEG) and atomic force microscopy (AFM, NT-MDT SOLVER P47H Polymer 300). Moreover, the band gap energy of the c-SiCN film was examined by photo-luminescence (PL) measurement system (Model: BiO-Rad RPM2000, U.K.) with He-Cd laser operating at 325 nm. Fig. 2 shows the XRD of the c-SiCN film on Si substrate. As seen, peaks for SiCN at 45.17° [20], and 69.15° for Si are found. This is because of the c-SiCN film is hetero-epitaxial growth on the Si substrate, which is evidenced by the superimposed diffraction patterns of crystalline Si (c-Si) and crystalline SiCN (c-SiCN) observed in the corresponding TEM pattern inserted in Fig. 2. Based on the AES depth profile and TEM pattern (inserted in Fig. 2), the *d* spacing is calculated and compared to that listed in ICDD (international center for diffraction data) [16], [21], and find the grown c-SiCN has a cubic structure with a FWHM (full width at half maximum) of 0.97°. Fig. 3 explains the measured photo and dark currents under room temperature and different reversed biases with HP4145B semiconductor parameter analyzer. The photocurrents were measured under the irradiation of 254 nm UV light source (Model: UVP, UVGL-58) with power of 0.5 mW/cm^2. The measured photo/dark current is 0.429 mA/0.221 μA for the homojunction under -5 volt bias. Furthermore, the PDCR is defined as PDCR = $((I_p - I_d)/I_d)$, where I_d is the dark current, and I_p is the photocurrent (i.e. the current under illumination). Fig. 4 presents the PDCR of n-SiCN/p-SiCN homojunction measured under -5 volt bias with and without an irradiation of 254 nm, 0.5 mW/cm^2 power UV light source for various measuring temperatures. At room temperature and under -5 volt bias (see the inset for detail), the PDCR is 1940, which is better than the reported ~ 1000 [22], or ~ 1500 [23] for 4H-SiC UV detector, and ~ 5.4 in metal semiconductor metal (MSM) structure [24] or ~ 60 in p-i-n structure [12] of β-SiC. With temperature increasing, the PDCR is decreased due to the raise of dark current in the depleted region. Physically, the dark current in elevated temperatures mainly comes from the thermal generation current based on the relation of $\exp(-E_g/2KT)$, where Eg is the band gap of c-SiCN (3.2 ~ 4.4 eV), T is operation temperature, and K is Boltzmann constant [25]. Thus, the dark current is increased rapidly as raising temperature, and results in the decreasing in high temperature. However, as temperature is raised up to 125 ℃, the PDCR still can be attained to 121.1. To our knowledge, this PDCR is the highest current ratio that has been reported except that prepared on the 6H-SiC [5], [6]. The better PDCR is ascribed to the reduced thermal generation dark current caused by the higher E_g of c-SiCN. Besides, the morphology was examined by the SEM top view photo of n-SiCN/p-SiCN homojunction and the AFM image shown in Fig. 5, respectively. The roughness (Rou) for the homojunction is 2.174 nm. These results indicate the deposited films are smooth and have a nice quality. We think the nice film quality also supports the better PDCR. Fig. 6 demonstrates the room temperature spectral responsivity of the n-SiCN/p-SiCN junction with 5 volt applied bias. The peak current responsivity is at 265 nm thus implies the n-SiCN/p-SiCN/p-Si device is preferred for deep UV detecting applications. Based on the measured current responsivity, we can obtain a quantum efficiency of 0.746. Additionally, the 329.2 nm (3.77 eV) peak with full width at half maximum (FWHM) of 30 meV (4.1 nm) as shown in the typical PL spectrum of SiCN/p-Si sample with 325 nm filter at room temperature (inserted in Fig. 6) demonstrates the c-SiCN film has a band gap of 3.77 eV, which is comparable to the 3.8 eV of microwave plasma enhanced chemical vapor deposition (MWCVD) deposited c-SiCN [18], and the 4.4 eV of the electron cyclotron resonance plasma enhanced chemical vapor deposition (ECRCVD) deposited c-SiCN [19]. It is the feature of the higher band gap of c-SiCN to enhance a good thermal stability, and thus the high PDCR of the developed junction [7], [24].

4. Conclusion

The n-SiCN/p-SiCN homojunction has been studied in detailed for low cost and high temperature ultraviolet (UV) detecting applications. The cubic crystalline SiCN films deposited on p-Si (100) substrate with RTCVD has a high band gap, and nice film quality, thus results in a photocurrent/dark current ratio of 1940 and 121.1 for room temperature, and at 125 ℃, respectively. The current ratio both in room and high temperature are better than that of the reported UV detectors with 4H-SiC or β-SiC, thus is more suitable for high temperature UV sensing applications.

Acknowledgement

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Figure Caption

Fig. 1 The schematic structure of the developed n-SiCN/p-SiCN homojunction.

Fig. 2 The XRD pattern for the c-SiCN film on p-Si substrate, and insert gives the corresponding TEM pattern.

Fig. 3 Photo-excited current and dark current of the developed n-SiCN/p-SiCN junction measured at room temperature under various reverse biases.

Fig. 4 The PDCR of n-SiCN/p-SiCN junction under various temperatures and 5V reverse bias, and insert gives the PDCR of n-SiCN/p-SiCN junction measured at room temperature under different reverse biases.

Fig. 5 The SEM photo and AFM image of n-SiCN film on p-SiCN/p-Si.

Fig. 6 The **c**urrent of spectral responsivity for the n-SiCN/p-SiCN junction under the room temperature, and 5V applied voltage. The inset shows PL spectrum of SiCN/p-Si with 325 nm filter measured at room temperature.

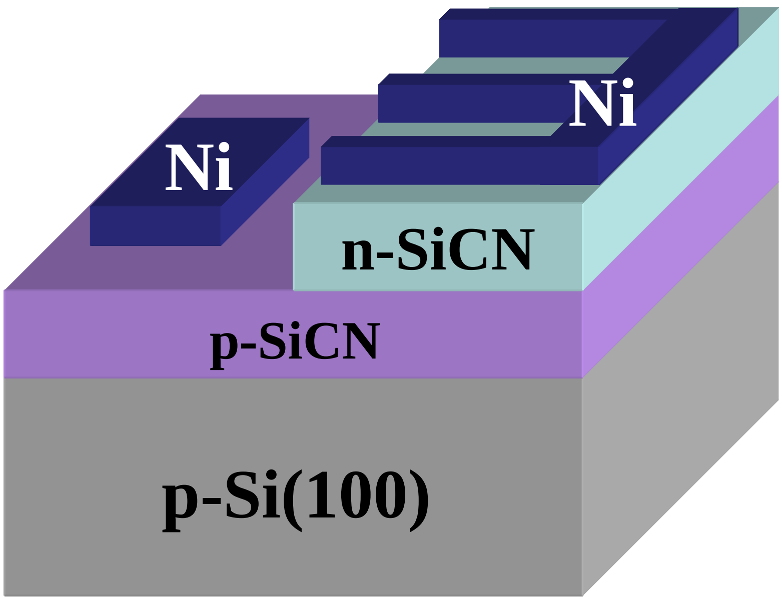

Fig. 1

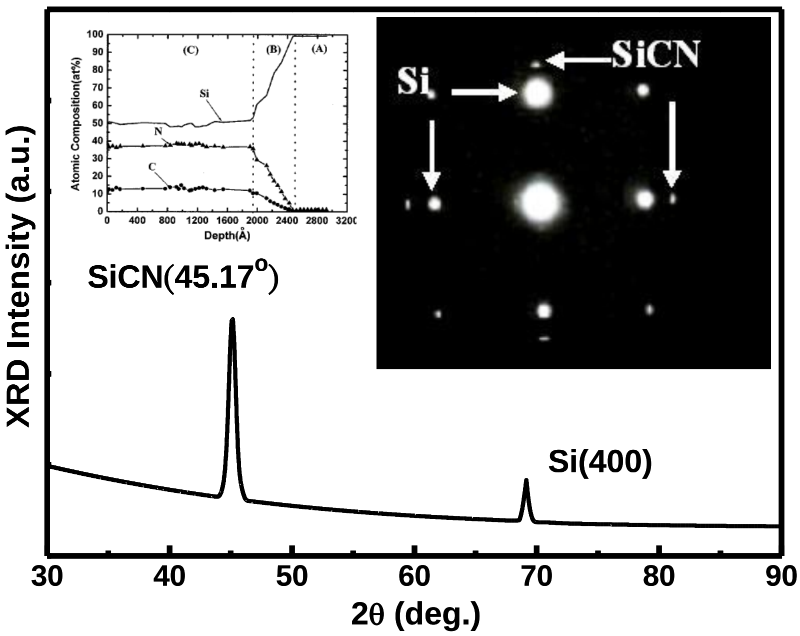
XRD Intensity (a.u.)
SiCN(45.17°)
Si(400)
Si
SiCN
30 40 50 60 70 80 90
2θ (deg.)

Fig. 2

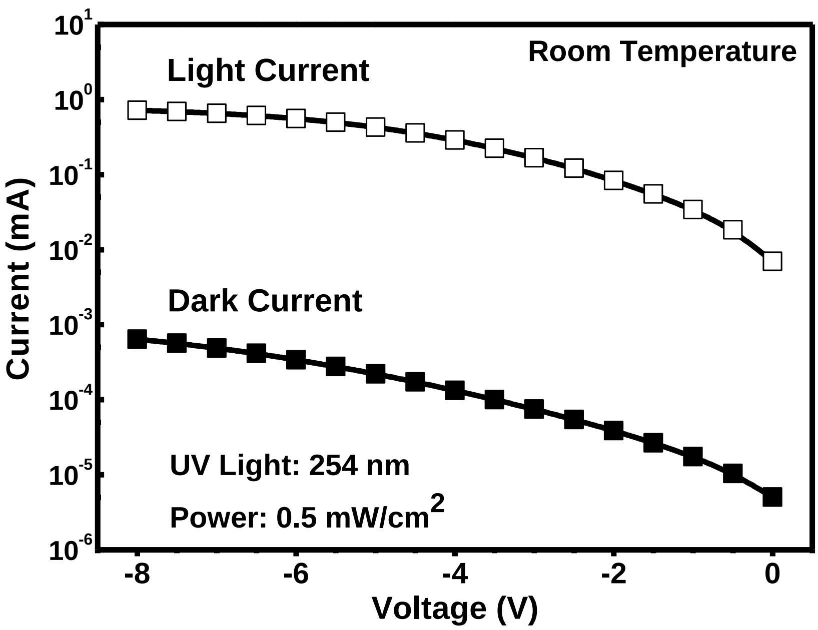
Room Temperature
Light Current
Dark Current
UV Light: 254 nm
Power: 0.5 mW/cm2
Current (mA)
Voltage (V)

Fig. 3

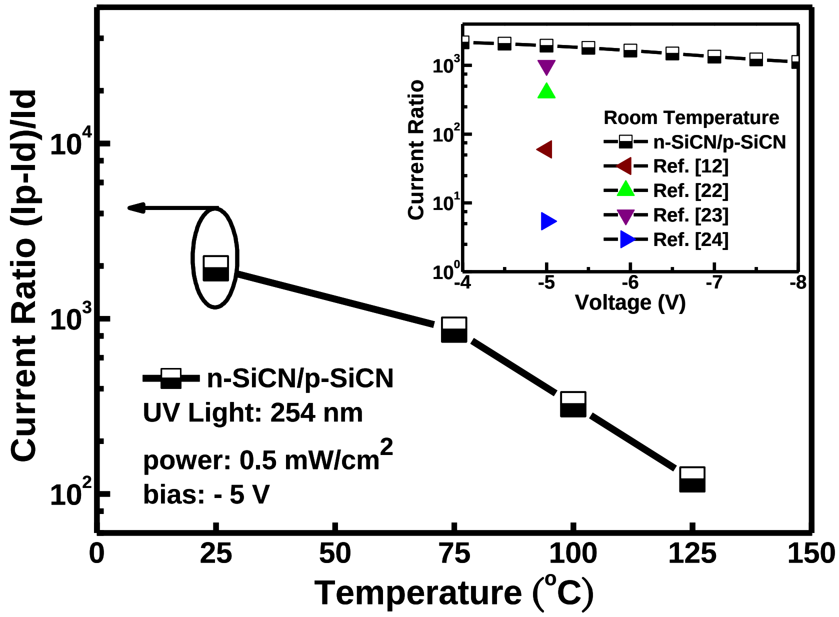
Current Ratio (Ip-Id)/Id
10^4
10^3
10^2
0
25
50
75
100
125
150
Temperature (°C)
n-SiCN/p-SiCN
UV Light: 254 nm
power: 0.5 mW/cm2
bias: - 5 V
Current Ratio
Voltage (V)
Room Temperature
n-SiCN/p-SiCN
Ref. [12]
Ref. [22]
Ref. [23]
Ref. [24]

Fig. 4

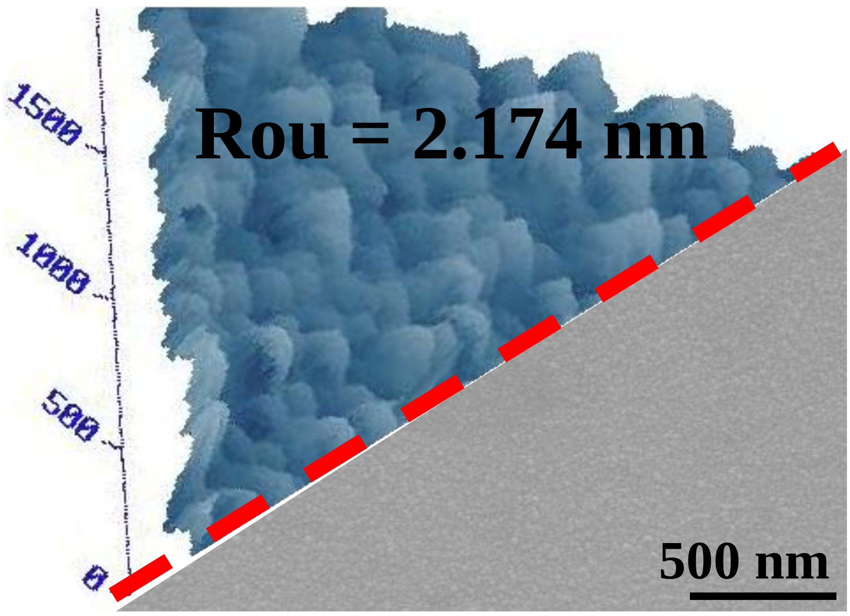
1500
1000
500
0
Rou = 2.174 nm
500 nm

Fig. 5

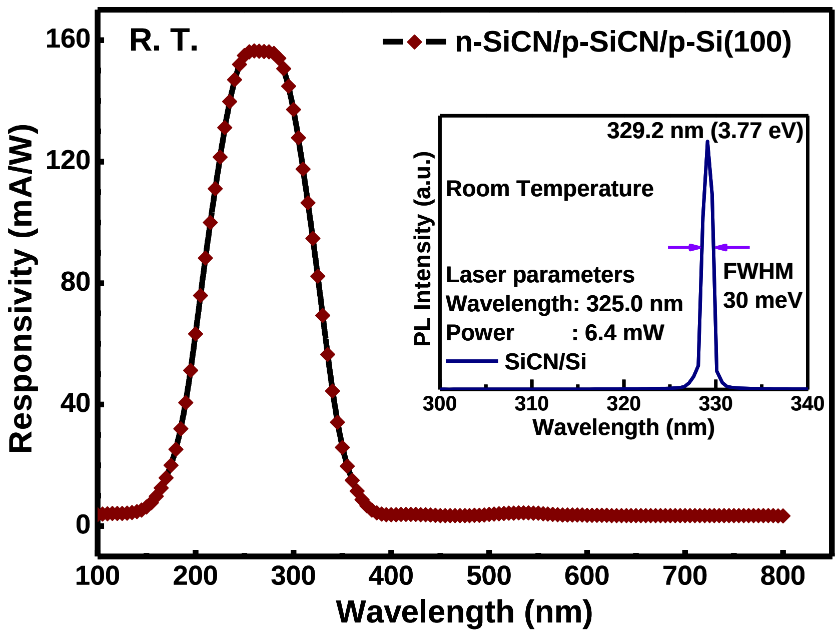
R. T.
n-SiCN/p-SiCN/p-Si(100)
Responsivity (mA/W)
Wavelength (nm)
0
40
80
120
160
100
200
300
400
500
600
700
800
329.2 nm (3.77 eV)
Room Temperature
Laser parameters
Wavelength: 325.0 nm
Power : 6.4 mW
SiCN/Si
FWHM
30 meV
PL Intensity (a.u.)
300
310
320
330
340
Wavelength (nm)

Fig. 6