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Responsivity spectra of GaN based Schottky type ultraviolet (UV) photodetectors with transparent electrode from the Vacuum Ultraviolet (VUV) region to soft X-ray (SX) region (10–100 nm, 124–12.4 eV) are described for the first time. The calculated transmittance of 10 nm-thick transparent Ni/Au electrode from the transmittance of Ti/Au membrane is about 0.5–0.7 in the VUV and SX region (10–100 eV). Thus it is considered that the 10-nm-transparent Ni/Au electrode is thin enough to transmit VUV and SX light into the transparent electrode. The value of responsivity in the SX region (at 13 nm) is about 0.05 A/W.

1 Introduction Ultraviolet (UV) detectors are one of the most attractive devices in the group III-nitride semiconductors. Better performance of UV photodetectors are demanded by various industrial applications such as flame detection, photolithography using short wavelength excimer laser, UV imaging, solar UV monitoring and so on. Currently, for the detection of UV light, Si-based photodetectors (SPDs) and photomultiplier tubes (PMTs) are mainly used. However, they have significant limitations due to the need of filters to stop low energy photons (SPD case), their degradation and lower efficiency (SPD case) and the need of a high voltage supply (PMT case). To overcome these limitations and to achieve solar-blind operation, III nitrides have been used as materials of UV photodetectors, recently. III nitrides are direct bandgap materials with GaN showing its absorption edge at 365 nm (E_g = 3.4 eV) and AlN at 200 nm (E_g = 6.2 eV) and with strong chemical bond compared with Si. Furthermore, AlGaN alloys have an advantage of the tunability of the detection edge by just varing the Al mole fraction. Several groups have reported on GaN- or AlGaN-based UV detectors [1], such as photoconductor [2, 3], p-n or p-i-n-type [4–6], the Schottky-based metal-semiconductor-metal-type [7–9], the Schottky type [10–15], avalanche type [16] and so on.

The advantage of Schottky barrier photodiodes compared with other structures is efficient absorption of UV light with shallow penetration depth like vaccum ultraviolet (VUV) or soft X-ray (SX) light because the depletion layer is formed in the vicinity of the interface between Schottky electrode and absorption layer. Schottky barrier GaN photodetectors were first reported by Khan et al. [10] who demon-

strated a Ti Schottky diode on p-type GaN. Chen et al. [11] reported a responsivity of 0.18 A/W by using 50 Å Pd as a Schottky barrier on n-type GaN. Monroy et al. [12] reported Schottky barrier UV photodetectors using Au electrode on epitaxial lateral overgrown GaN. The high quality absorption layer resulted in a lower dark current and a high UV/visible contrast. These photodetectors show responsivities between 200 and 365 nm.

VUV and SX light are expected to be utilized in the new photolithography technique, such as using the light of an ArF laser (λ = 193 nm), an F_2 laser (λ = 157 nm) and an EUV light (extreme UV, λ = 13 nm). Currently, for the detection of VUV or SX light, Si-based photodetectors (SPDs) [17] are mainly used. However, they have significant limitations due to some problems previously mentioned. III nitrides based photodetectors are expected to overcome these limitations. The fabricated GaN based UV photodetectors have possibilities of being used in steppers for future photolithography systems with short wavelength mentioned above. However there are only few reports on the detection of VUV light (<25 eV) by GaN based photodiodes [9, 13–15] and there are no reports on that of VUV and SX light (>25 eV).

In this study, the responsivity spectra of GaN based Schottky type UV photodetectors with transparent electrode from the VUV region to SX region (10–100 nm, 124–12.4 eV) are described for the first time.

2 Experimental procedure The UV detectors with a transparent Schottky electrode consist of a 3-μm-thick n-GaN layer (n = 2.0×10^{18} cm^{-3}) and a 1.5-μm-thick i-GaN layer (n = 1.0×10^{16} cm^{-3}) on a (0001) sapphire substrate. These layers are grown by metalorganic vapor phase epitaxy (MOVPE). The Ni/Au Schottky contact is deposited on i-GaN. The diameter of detectors is 6.5 mm. The details of samples are previously mentioned [14, 15].

The responsivity spectra of UV detectors are characterized by measuring the photocurrent illuminating monochromatic VUV and SX light at the beam line 5B (BL5B) of the UVSOR Facility, Institute for Molecular Science. BL5B has a plane grating which energy range is from 2 to 200 nm (6–600 eV). Usually the monochromatic lights by grating contain higher order light. In order to characterize responsivity exactly, the cut off filters are needed for eliminating higher order light. In this study, freestanding dielectric or metal films such as Ti, Ti/Al/Ti and SiN are fabricated and used as filters. Prior to characterization of responsivity spectra, the transmittance spectra of Ti, Ti/Al/Ti and SiN films are measured to characterize filter characteristics of freestanding films. Furthermore, those of Ti/Au (thickness 50 nm) using these filters are measured to characterize the transmittance of transparent Schottky electrode.

3 Results and discussion Transmittance spectra of freestanding dielectric or metal filter are characterized. Figure 1 shows transmittance spectra of Ti, Ti/Al/Ti and SiN films. Each thickness of films is

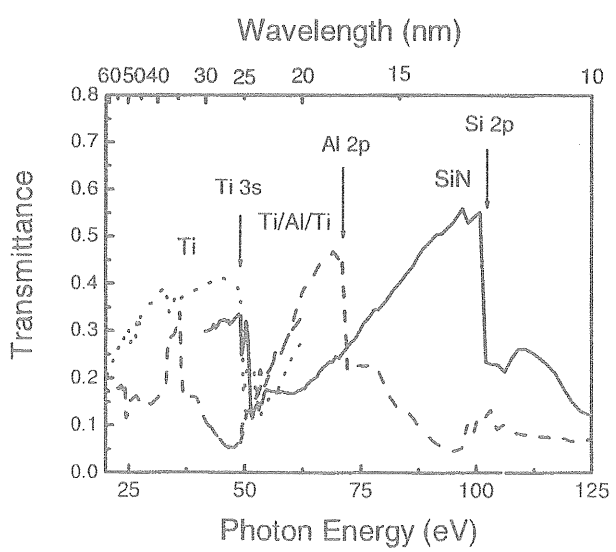

Fig. 1 Transmittance spectra of Ti, Ti/Al/Ti and SiN membrane.

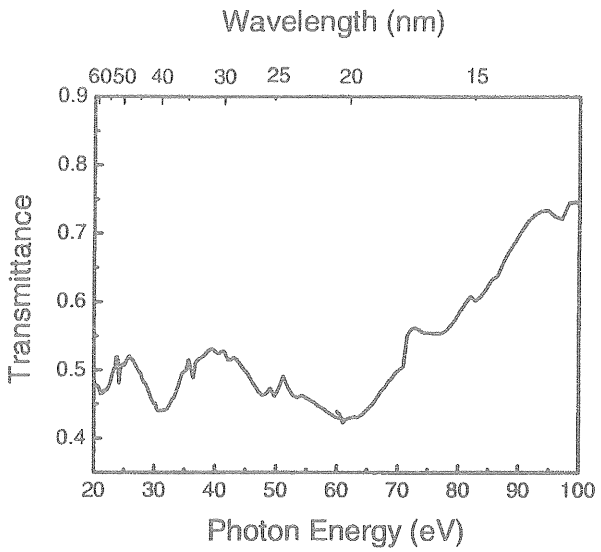

Fig. 2 Transmittance spectra of transparent Schottky electrode calculated from that of Ti/Au membrane.

30 nm, 80 nm and 100 nm, respectively. Clear contrasts of transmittances were observed at 50 eV, 75 eV and 100 eV, respectively. These values are correspondent to the absorption energy of Ti 3s, Al 2p and Si 2p. Thus, it is found that these freestanding films can be used as cut off filters for higher order lights and responsivity spectra can be measured less than 100 eV using these filters.

Based on the results of Fig. 1, the transmittance of a transparent Schottky electrode is characterized by using a Ti/Au membrane. The transmittance spectra of transparent Schottky electrode are calculated from that of 50-nm-thick-Ti/Au membranes. Ti layer and Ni layer are much thinner than the Au layer. Thus, in this experiment, Ti/Au membrane is used instead of a Ni/Au transparent Schottky electrode. Figure 2 shows the calculated transmittance of the Schottky electrode. The calculated transmittance of Schottky electrode is estimated about 0.5–0.7 in the VUV and SX region (20–100 eV). Therefore, it is considered that 10-nm-thick Ni/Au is thick enough to transmit VUV and SX light into the transparent electrode.

Using these filters and transparent electrode, the responsivity spectra of GaN UV detectors are characterized. Figure 3 shows the responsivity spectra of samples. In this figure the responsivity spectra in near UV and VUV regions (<25 eV, using BL7B) [17] are also included. No responsivity at the energy lower than 3.4 eV (the absorption edge of GaN) can be clearly observed. This indicates that these detectors can be used in the near UV, VUV and SX region. The ratio of responsivity between UV and VIS regions is about 5×10^3. The maximum responsivity of this detector is about 0.10 A/W at $h\nu = 3.5$ eV. The continuity of spectra around 25 eV between different beam lines is good. The responsivity in the VUV region

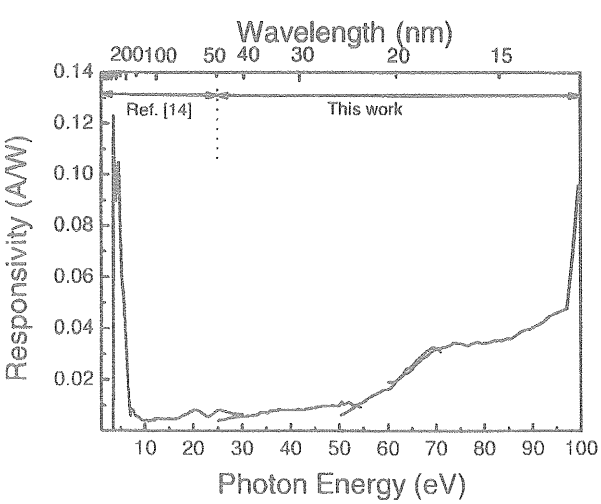

Fig. 3 Responsivity spectra of GaN UV detectors.

(10–50 eV) is about 0.01 A/W. The larger responsivity is found in the VUV-SX region (>50 eV). It is considered that the high responsivity in VUV-SX region is due to the increased transmittance of Ni/Au with increasing photon energy. The value of responsivity in the soft X-ray region (@13 nm for EUV lithography system) is about 0.05 A/W.

4 Conclusions In conclusion, the responsivity spectra of GaN based UV detectors are obtained for the VUV and SX light for the first time. The freestanding dielectric or metal filters such as Ti, Ti/Al/Ti and SiN are available to cut off higher order lights. The transmittance of 10-nm-thick Ni/Au transparent electrode is estimated about to 0.5–0.7 in the VUV-SX region, which indicates that this transparent electrode is thin enough to transmit VUV and SX light into absorption layer. Finally, the responsivity of about 0.01–0.05 A/W in VUV and SX regions is obtained by using these filters and transparent electrode.

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