# Characterization of AlN metal-semiconductor-metal diodes in the spectral range of 44–360 nm: Photoemission assessments

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The absolute responsivity of a metal-semiconductor-metal (MSM) photodiode based on high quality AlN material has been tested from the vacuum ultraviolet (vuv) to the near UV wavelength range (44–360 nm). The metal finger Schottky contacts have been processed to 2 $\mu$m in width with spacing between the contacts of 4 $\mu$m. In the vuv wavelength region, the measurement methodology is described in order to distinguish the contribution of the photoemission current from the internal diode signal. In the wavelength range of interest, AlN MSM is sensitive and stable under brief vuv irradiation. The MSM shows a 200/360 nm rejection ratio of more than four orders of magnitude and demonstrates the advantages of wide band gap material based detectors in terms of high rejection ratio and high output signal for vuv solar observation missions. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2834701]

Present vacuum ultraviolet (vuv) detectors based on silicon material exhibit serious limitations in performance, technology complexity, and lifetime. For the next envisaged space mission planned to study the Sun, the *Solar Orbiter*, innovative photodetectors based on wide band gap semiconductors are crucial. Photodetectors fabricated from various wide bandgap semiconductors have been reported. Among them, SiC,[1] GaN,[2] and II-VI compound-based detectors[3] show a cutoff wavelength longer than 300 nm, whereas AlGaN (Ref. 4) and diamond-based[5] devices present a significantly shorter cutoff wavelength at 229 and 225 nm, respectively. Recently, high quality AlN metal-semiconductor-metal (MSM) and Schottky photodiodes have been demonstrated by the research group of the Kansas State University.[6,7] In this work, we report on the absolute radiometric characteristics of the AlN MSM ongoing studies. By its nature, AlN semiconductors are promising for the development as the photosensitive material for Solar vuv photon detection (spectral range of interest $10 < \lambda < 120$ nm). AlN has figure of merit that are several orders of magnitude higher compared to silicon semiconductor since it provides high radiation hardness (whole mission lifetime preserved), solar blindness with a $\lambda_{cutoff} \cong 203$ nm, chemical and thermal stabilities, and no need of cooling (room temperature operation).

The purpose of this work is to demonstrate the suitability of the AlN MSM photodiode for vuv applications and consecutively for solar observation missions in order to have a solid detector baseline for its radiometers and telescopes. The detector is based on a 1.5 $\mu$m thick AlN epilayers grown on sapphire substrate using metal organic chemical vapor deposition. The device layer structure is schematically shown in Fig. 1(a). Homoepitaxial growth procedure details are given elsewhere.[6] Three AlN MSM samples were connected together in parallel to form a larger single-pixel device. The fabricated detector has $3 \times (0.1 \times 0.08)$ mm$^2$ as an active area. The interdigitated fingers for Schottky contacts have been designed to 2 $\mu$m in width with spacing between the contacts of 4 $\mu$m. Metallization of contacts is Pt/Au with thicknesses of 10/200 nm, respectively.

The AlN photodiodes have been characterized in the normal incidence (NI) beamline of the *Physikalisch-Technische Bundesanstalt (PTB)* laboratory at the storage ring *Berliner Elektronenspeichering-Gesellschaft für Synchrotronstrahlung (BESSY II)*. The detector calibration facility provides a synchrotron beam, monochromatized by a NI monochromator with a spectral resolution of about 1% of the wavelength. To cover a wide spectral range from 40 to 240 nm, different filters and beamline mirrors are used to suppress higher order contributions to the selected bandwidth.[8,9] The

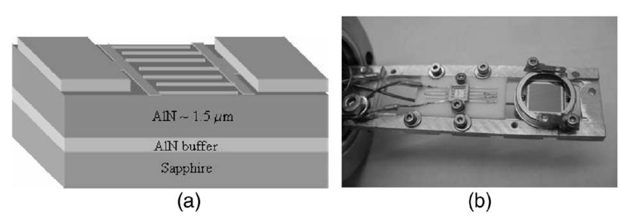


FIG. 1. (a) Schematic representation of the device layer structure and (b) photograph of the AlN MSM photodiode mounted and insulated on a teflon plate inside the manipulation stages holder together with the silicon photodiode reference detector.

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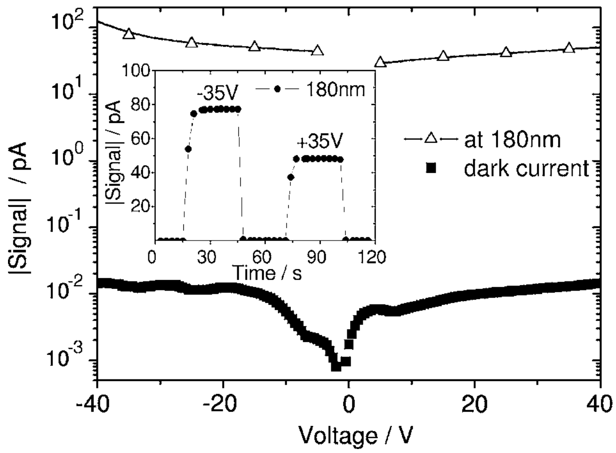


FIG. 2. *I-V* characteristics of AlN MSM photodiode at room temperature. The inset shows the absolute signal (pA) as a function of time at 180 nm (400 nW radiant power).

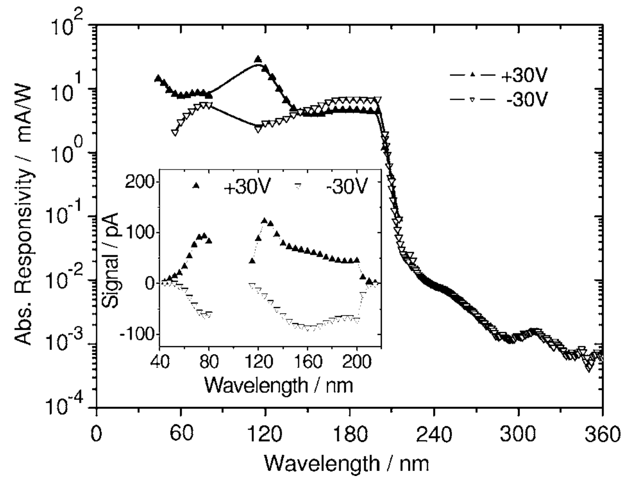


FIG. 3. Absolute responsivity (mA/W) of AlN MSM at ±30 V bias between 44 and 360 nm. The inset shows the absolute signal (pA) between 44 and 225 nm.

detector calibration chamber at the end of the beamline is an ultrahigh vacuum chamber with manipulation stages, which allow to raster the sample area and to toggle between test and reference detectors, as shown in Fig. 1(b). The spot size of the beam at the location of the samples is approximately $1\times 2$ mm$^2$, depending slightly on the chosen wavelength. The radiometric uncertainty of the measurements was estimated to be better than a few percent in absolute terms. Individual measurements were repeated to check stability and reproducibility. For the longer wavelength range ($\lambda > 200$ nm), monochromatic light was generated with a 40 W deuterium lamp. The data from 200 to 360 nm, measured on a relative scale were matched to the absolute data from PTB/BESSY II.

For the vuv photoresponse measurement, a well know parasitic phenomenon is the photoemission where photogenerated electrons have enough energy to escape from the device. In a typical vuv setup, the photodetector is housed in a metal vacuum chamber that is grounded to the earth and is usually common to the ground terminal of the electrometer. The photoelectrons emitted from the photodetector surface (metal contact and AlN material) form an additional current circuit in addition to the internal photocurrent, $I_d$ generated in the photodiode. This situation automatically and unintentionally provides a three terminal configuration and, therefore, it is important to consider if the measuring circuit includes the photoemission current path or not. To distinguish the contribution of the photoemission current from the wanted signal, all measurements should be repeated with the other side grounded.[10,11] If in both cases, the same signal is measured (in absolute terms), we can conclude that there is no photoemission contribution to the signal. Note that the photoemission signal is likely dominated by AlN but also by the Au interdigitated fingers metal emission.

Typical current-voltage (*I-V*) characteristics are checked at room temperature and show a negligibly small dark current of 13 fA at −30 V (Fig. 2). We plotted as well the photocurrent at 180 nm where the photoemission current contribution should be insignificant. The measured signal was stable between −35 and +35 V, as shown in the inset of the Fig. 2 and no persistent photoconductivity was observed. Note that, in principle, MSM photodetector is symmetrical and for opposite biases the photocurrent signal is expected to be equal (in absolute terms). In practice, even if there is no photoemission current, there is still a small offset due to defects in the material and/or on finger contacts.

The absolute spectral responsivity was performed in the ranges from 44 to 80 nm and 115 to 225 nm for both polarities (−30 and +30 V) to assess the photoemission contribution. As seen in Fig. 3, the responsivities curves at ±30 V show the AlN band edge to be around 203 nm, i.e., ~6.1 eV and displays a rejection ratio 200/360 nm of more than four orders of magnitude. For clarity, we did not plot the estimated error bars to the data points. Between $170 \leqslant \lambda \leqslant 200$ nm, the photoresponse looks stable with a responsivity of approximately 6.8 and 4.5 mA/W at $U=-30$ V and $U=+30$ V bias, respectively. Then, the photoresponse increases or decreases depending on the applied voltage due mainly to the photoemission current contribution. For $U=+30$ V, the photoemissive threshold energy of AlN $E_{t_{\mathrm{AlN}}}=8.1\pm 0.25$ eV can be approximately determined. $E_{t_{\mathrm{AlN}}}$ is defined as the energy distance from the valence band maximum to the vacuum level and is related to the energy gap $E_{g_{\mathrm{AlN}}}$ (6.1 eV according to Fig. 3) and the electron affinity $\chi$ by the relation $E_{t_{\mathrm{AlN}}}=E_{g_{\mathrm{AlN}}}+\chi$. This equation yields also to a lower limit for the electron affinity, namely, $\chi \geqslant 2.0\pm 0.25$ eV (assuming no band bending at the semiconductor-metal interface). Our finding is in good agreement with the value of $2.1\pm 0.3$ eV estimated by UV and x-ray photoemission spectroscopy.[12] At around 115 nm, the photoresponse, for $U=+30$ V bias, reaches a maximum responsivity of 30 mA/W (with a corresponding external quantum efficiency of 34%) and a minimum of 2.4 mA/W for $U=-30$ V bias. It then decreases or increases until 80 nm for $U=+30$ V and $U=-30$ V bias, respectively. This value is still close to the ionization threshold of almost any material which means that the absorption is high with the generation of a high number of electrons close to the surface. For $U=-30$ V, we still have a positive and high photoresponse. Between 60 and 80 nm, the responsivity for $U=+30$ V is nearly constant with a photoresponse of 8.45 mA/W at around 75 nm. The photoemission process is usually described using a three step model, i.e., photoabsorption, photoelectron transport toward the surface and electron escape into the vacuum. Here, we can add one step more where the photoemitted electrons are pulled back to the device due to

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the high positive applied voltage, i.e., +30 V. They can then participate or not (due to carriers recombination) to the internal photocurrent diode. Note that such pulled back effect was already reported for diamond detectors at +20 V bias.[13] This can explain also the absence of photoresponse peak at around 70–80 nm as already observed[14,15] for photodetectors with low applied bias, i.e., 0–5 V. For $\lambda \leqslant 60$ nm, the responsivity (for $U=+30$ V) starts to increase again. This is related to an increase of the number of electron-hole pairs created per absorbed photon $\eta(\lambda)$ which can be assumed higher than unity. For sufficiently high photon energies, secondary ionizations are energetically possible and the ratio of photon energy to the number of electron-hole pairs generated becomes constant $\eta(\lambda)=\lambda c/\lambda$ for $\lambda \leqslant \lambda c$. For AlN a value of $\lambda c \cong 65.8$ nm, i.e., $\sim 18.85$ eV is predicted by the Klein formula.[16] For $U=-30$ V, the photoresponse becomes negative. The negative photoresponse should be seen in relation to the photoemission current which is higher than the internal diode current but note that both signals are very low, i.e., picoampere range, thus, leading to a high uncertainty here.

In summary, the responsivity and stability of AlN MSM detector have been tested in the vuv region. In the wavelength range of interest, AlN MSM is reasonably sensitive and stable under brief irradiation with a negligible dark current. It indicates a 200/360 nm rejection ratio of more than four orders of magnitude. To ultimately get rid of the annoying impact of photoelectrons, we recommend to bias the whole electrical circuit to energy higher than the maximum kinetic energy that the electron can acquire after leaving the surface, e.g., some tens of electron volts. We expect advantages by operating the AlN MSM detector at high positive bias voltages maximizing the output signal and reducing the electron escape probability.

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