Toward AlGaN Focal Plane Arrays for Solar-Blind Ultraviolet Detection

Robert Rehm,* Rachid Driad, Lutz Kirste, Stefano Leone, Thorsten Passow, Frank Rutz, Lars Watschke, and Andreas Zibold

Missile approach warning (MAW) systems of airborne military platforms require ultrasensitive detection capabilities in the solar-blind UV regime below 280 nm. Today, these needs are answered with UV photomultiplier tubes, which are bulky, complex, and require external filtering to suppress clutter signatures beyond 280 nm. This study investigates whether AlGaN focal plane array (FPA) detectors may develop into a viable alternative. The compact, lightweight, all-solid-state solution promises intrinsic solar blindness and excellent out-of-band suppression ratios realizable at affordable costs on large-area substrates. Yet, does today’s state of technology allow mastering the fabrication processes so that the electrooptical performance is sufficient to achieve the required sensitivity? Herein, three device wafers are grown by metalorganic chemical vapor deposition and subsequently processed into detector arrays with a spatial resolution of 640 × 512 pixels on a 15 μm pitch. After hybridization with an off-the-shelf capacitive transimpedance input amplifier (CTIA) read-out integrated circuit (ROIC), their electrooptical performance is characterized. The characterized FPAs show a very low percentage of defective pixels, excellent linearity at high photon fluxes, and, at low flux, their already remarkable sensitivity is limited by the off-the-shelf CTIA ROIC. Therefore, with further improvements MAW systems based on AlGaN FPAs seem feasible. and man-made sources prevail. However, due to scattering on molecules and aerosols photon propagation in the atmosphere is limited. Therefore, MAW systems require ultra-high-performance photon detectors that ideally achieve close to single photon detection capability to deliver maximum detection range and early warning for initiating measures to protect the platform. Today, MAW system requirements are answered with UV photomultipliers. These comprise UV optics, filters, a photocathode, a multi-channel plate, a luminescence screen, and an optical detection path, e.g., based on fiber optics and a Si charge-coupled device detector. Therefore, UV photomultipliers are complex, bulky, and require a high operating voltage. Yet, they do offer the required photon detection capability along with a very low dark count rate.

This article investigates whether an alternative compact, light-weight, all-solid-state alternative solution might be achievable with backside-illuminated AlGaN focal plane array (FPA) detectors, which comprise a 2D AlGaN detector array flip-chip hybridized to a silicon capacitive transimpedance input amplifier (CTIA) read-out integrated circuit (ROIC). For an alloy composition slightly in excess of 40% of Al, the bandgap energy corresponds to the required long-wavelength cut-off around 280 nm. The short-wavelength cut-on can be tailored by the Al content in another AlGaN filtering layer grown beneath the absorber. This allows the fabrication of intrinsically solar-blind UV detectors with excellent out-of-band suppression, circumventing the need for complex external filters that plague today’s photomultiplier-based systems. Further fundamental advantages of AlGaN detectors include a high quantum efficiency, radiation hardness, and a high speed of response. The epitaxy of high-quality AlGaN is performed by multiwafer metalorganic chemical vapor deposition (MOCVD) on transparent large-area sapphire substrates offering low-cost potential.

The semiconductor device most closely resembling photomultipliers is the avalanche photodiode (APD). Although advanced APD concepts, where photon absorption and carrier multiplication are spatially separated, are very complex to design and grow, simple p–i–n-type APDs suffer—under high operating bias—from the Franz–Keldysh effect in the intrinsic region, leading to an unwanted redshift of the long-wavelength absorption edge. Furthermore, achieving narrow, homogeneous

1. Introduction

Critical defense applications, e.g., missile approach warning (MAW) systems in airborne platforms, require ultrasensitive detection capabilities in the solar-blind UV range below 280 nm. In this regime, solar signatures are suppressed by extinction in the atmosphere. Thus, in contrast to MAW systems operating in the mid-wavelength infrared between 3 and 5 μm, the solar-blind UV regime offers a homogeneous background free of natural clutter.

Dr. R. Rehm, Dr. R. Driad, Dr. L. Kirste, Dr. S. Leone, Dr. T. Passow, Dr. F. Rutz, Dr. L. Watschke, A. Zibold
Business Unit Photodetectors
Fraunhofer Institute for Applied Solid State Physics IAF
Tullastr. 72, 79108 Freiburg, Germany
E-mail: robert.rehm@iaf.fraunhofer.de

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distributions for the multiplication gain, operation voltage, and dark current under high-reverse-bias operation are certainly very challenging for any APD FPA approach. Therefore, the investigation of ordinary photodiode technology was pursued. Provided that the dark current and noise of the devices are adequately low, ordinary photodiodes combined with an ROIC with a sufficiently small read-out capacitor and a very low read-out noise might attain close to single photon detection capability with standard 14-bit analog-to-digital conversion. For cost-saving reasons the initial investigations described subsequently rely on an off-the-shelf ROIC that was originally developed for low-light-level applications in the short-wavelength infrared regime with p-on-n InGaAs photodiode arrays. The chosen ROIC supports a spatial resolution of 640 × 512 pixels with a pixel pitch of 15 μm (640 × 512/15) and features highly linear CTIA circuitry nominally with an integration capacitance of 10 fF and a charge handling capacity of about 110 000 electrons. Prior publications on AlGaN FPAs for the solar-blind UV regime are rather sparse and did not exceed a maximum resolution of 320 × 256/30.\textsuperscript{1–4}

This article is organized as follows. Section 2 presents the fabrication of the first generation of 640 × 512/15 AlGaN FPAs, i.e., MOCVD growth, frontside processing, and hybridization. Section 3 deals with the electrooptical characterization of test devices and FPAs. Finally, the results are summarized and conclusions are drawn.

2. Fabrication

2.1. MOCVD Growth and Nondestructive Characterization

Realizing solar-blind AlGaN photodiode arrays with ultralow dark current for achieving close to single photon sensitivity without employing internal avalanche gain is challenging. Of particular importance for a carefully optimized electrooptical detector performance are detailed studies of the interplay between vertical device design, choice of substrate, MOCVD growth parameters as well as formation of point defects and threading dislocations. C-plane (0001)-oriented, epi-ready commercial hydride vapor phase epitaxy (HVPE) AlN-on-sapphire template substrates with an AlN thickness around 500 nm, high optical transmission, single-side-polished, low off-cut angle of 0.2°, and 2 in. wafer diameter were employed. Growth of the vertical device structure commenced with a 150 nm thick buffer with continuously graded Al composition (from 100% to slightly above 40% Al as desired for the active region). B) a step-graded buffer (with nominal steps of 80% and 60% of Al, both AlGaN layers with a thickness of 70 nm), and C) an abrupt switch in Al composition (by simply omitting this buffer layer). After the buffer, the active n⁺–i–p⁺ region was grown without any intentional changes in Al content. While the n⁺-AlGaN:Si contact layer, doped with a Si atom concentration of 1 × 10¹⁸ cm⁻³, had a thickness of 350 nm, the intrinsic, residually n-type i-AlGaN layer was realized with a thickness of 180 nm. Next, a 30 nm thin p⁺-AlGaN: Mg layer, doped with a Mg atom concentration of 1 × 10¹⁹ cm⁻³, followed by a 70 nm thick p⁺-GaN:Mg ohmic contact layer ended the vertical device structure. The dopant concentrations were verified by secondary-ion mass spectrometry (SIMS).

Following MOCVD growth the as-grown material has been nondestructively characterized by various analytical methods. First, high-resolution X-ray diffraction (HRXRD) was employed. Figure 1 shows 1124 reflection reciprocal space maps of the three structures A to C described earlier. The continuously graded (left panel), step-graded (middle panel), and abrupt buffers (right panel) can be clearly distinguished and the Al content of the active region was determined to A) 42.5%, B) 40.8%, and C) 43.4%, respectively. The degree of relaxation of the partially relaxed active regions amounts to A) 17.9%, B) 24.2%, and C) 17.1%. Additional ω-scans of the 0002 and 1012 reflexes revealed

Figure 1. 1124 reciprocal space maps of the device wafers with vertical structure A (left), B (middle), and C (right). Extracted AlGaN compositions are noted in the graphs.
full-width-at-half-maximum (FWHM) values of A) 254 and 459, B) 269 and 522, and C) 276 and 479 arcsec, respectively. **Figure 2** compares Normarski microscopy images of the three device wafers for 200× magnification. The surface morphology of all three variants appears very similar and the defect density appears low. Evidently, the thin, fully relaxed GaN:Mg ohmic contact capping layer is not completely coalesced on any of the three device wafers. The photoluminescence (PL) spectra shown in **Figure 3** were obtained under frontside illumination with a 193 nm excimer laser. The PL peaks of the active regions are A) 275, B) 278, and C) 273 nm, respectively. In accordance with the somewhat lower Al-content, device wafer B shows a slightly longer PL peak wavelength in comparison to the other two device wafers. While the strong and broad frontside-illuminated PL around 365 nm clearly originates from the GaN:Mg cap, the PL signal around 330 nm is attributed to defect-related luminescence. Laser excitation is confined to the topmost layers due to the high absorption coefficient and no PL signal is received from the step-graded buffer layers with 60% and 80% Al for the device wafer with vertical structure B. Clearly, the PL signal of the active region is significantly reduced on this wafer compared to the other two. This observation together with the larger FWHM of the 1012 reflex may indicate a lower structural layer quality due to an increased density of edge dislocations. For the two wafers with vertical structures A and C no strong dissimilarities in terms of structural quality were observed with the non-destructive characterization methods presented here.

2.2. Frontside Processing and Hybridization

The p–i–n photodiode vertical layer stacks were processed into mesa-type devices with conventional photolithography and dry chemical mesa etching employing a dielectric passivation. Following a high-temperature Mg activation step, the entire processing comprised six mask layers for realization of Ni/Au p-contacts, hard-mask-based mesa etching and SiO₂ passivation, deposition of V / Al / V / Au n-contacts as well as Ti / Pt / Au diffusion barriers and bond metallization. **Figure 4** shows an image of a fully processed detector wafer. In the central part of each 2 in. wafer four 640 × 512/15 solar-blind UV detector arrays were realized. The outer areas were clustered with test structures. While the 640 × 512/15 detector array design is pin compatible to the off-the-shelf CTIA ROIC described in the Introduction, the test patterns match with the design of a 24-pin probe card installed on a semiautomated wafer probe station.

After completion of the frontside process, the individual detector arrays were diced into individual chips using a laser cutting tool equipped with a UV picosecond laser. In bumps were realized on the Si-ROIC wafer and a flip-chip hybridization process was conducted by an external service provider with standard process parameters for IR FPAs. The 430 μm thick sapphire substrate was kept unthinned for the subsequent electrooptical characterizations of the hybrid FPAs. The FPA backside was left without an antireflection (AR) coating.

3. Electrooptical Characterization

3.1. Test Devices

For characterization of the photocurrent and external quantum efficiency (EQE) a broad-band (170 nm–vis) UV–vis plasma...
source coupled to a monochromator was used. A calibrated commercial Si photodiode served to quantify photon flux from the source. The setup allowed both characterization under frontside illumination on test devices with an optical window in the top p-contact metallization as well as backside device illumination from the substrate side. For a logarithmic axis of ordinates, Figure 5 shows test device EQE spectra measured under backside illumination for all three investigated vertical structures at room temperature. The unbiased spectral EQE peak value is clearly below the roughly 80% that have been shown in the literature before for backside-illuminated solar-blind AlGaN FPAs.\textsuperscript{[5]} The suboptimal EQE is mainly attributed to the vertical structural design, which had not been optimized in the way taught in the given reference. Despite that, already now an excellent out-of-band suppression for radiation in the non-solar-blind regime beyond 280 nm is evident from Figure 5. As described in the Introduction, the shape of the EQE toward higher photon energies results from the transmission properties of the underlying layers.

With the samples mounted in a Faraday cage on a vibration-isolated stage, dark current measurements were performed on quadratic test devices with a size of $50 \times 50 \, \mu m^2$ at room temperature using a Keysight B2987A atto-amperemeter. Due to their ultrahigh impedance under dark conditions, the devices’ $RC$ time constant is huge. Therefore, recording conventional $I$–$V$ characteristics is impractical and instead the dark current was recorded at a fixed reverse bias value of $-200$ mV versus time. Figure 6 shows data collected for all three vertical device designs compared in this study. Within the first few minutes, the measured dark current value showed the expected $RC$-related decay before plateauing out. Yet, even in the plateau region the measured value went along with significant noise associated with persisting imperfections of the measurement setup. Despite that, the $50 \times 50 \, \mu m^2$ test devices exhibited a dark current level clearly below 1 fA. Considering the fact that their area is more than an order of magnitude smaller, the bulk dark current of small-sized FPA pixels with an active area of about $10 \times 10 \, \mu m^2$ was expected to be clearly less than 0.1 fA. Since the plateau dark current values shown in Figure 6 are setup limited, the FPA pixel dark current level might be even much smaller than that. A reverse bias of about $-10$ V was required for the dark current to exceed 10 fA in $50 \times 50 \, \mu m^2$ test devices.

3.2. Focal Plane Arrays

After hybridization, the FPAs were mounted in 84-pin chip carriers (see Figure 7). A Pulsed Instruments System 7700 automated imaging test station was used to operate the ROIC for electrooptical FPA characterization. The system has an A/D converter offering 14-bit resolution. To illuminate the FPAs a high-brightness, broad-band (170 nm–vis) plasma source coupled to a monochromator was employed. The fiber-coupled output of the monochromator was fed into a collimator followed by homogenization optics based on two microlens arrays to generate a flat-top beam profile in the focal plane. Between the homogenization optics and the focal plane a switchable filter wheel was installed that carried neutral density optical filters allowing to selectively attenuate the photon flux by up to eight orders of magnitude. The flux in the focal plane was measured with an externally calibrated Si photodiode. In the focal plane the nonattenuated photon flux around the responsivity peak of all
samples at 276 nm amounts to about $1.1 \times 10^8$ photons per second per area of an active FPA pixel.

To determine the current generated in any FPA pixel under a set illumination condition, in each case 50 frames of data were taken for a set of four different integration times. The averaged pixel signal over these 50 frames is expected to depend linearly on the integration time. From the slope of this dependence the current flow under the set illumination condition can be calculated. For dark conditions as well as source attenuation levels of two orders of magnitude and more, integration times of 26.2, 78.6, 131.1, and 262.1 ms were used. For source attenuations less than two orders of magnitude as well as under nonattenuated illumination, the selected integration times were reduced to 0.819, 1.638, 2.46, and 3.28 ms to prevent saturation of the ROIC capacitors.

To first characterize the behavior of the ROIC, a randomly selected bare Si-ROIC chip (w/o AlGaN detector array) was mounted on an 84-pin chip carrier. Figure 8 shows current histogram data for the leakage level under dark conditions (left panel) as well as under full nonattenuated UV flux from the high-brightness source with the monochromator set to a central transmission wavelength of 276 nm (right panel). Presumably caused by MOSFET body diodes that are associated with several transistor switches in the unit cell of the ROIC, the histogram data of this ROIC peaks around a value slightly below 2 fA under dark conditions. Even for full impinging flux on the frontside of the Si ROIC the peak value merely shifts by about 0.6 fA. No dedicated thermal stabilization was used for these characterizations and the observed changes might be caused partly by temperature fluctuations in the lab. Evidently, as a result of its suitable design, the chosen off-the-shelf CTIA ROIC is highly insensitive to UV irradiation. Yet, its room temperature leakage current around 2 fA sets a lower limit for the identification of possible dark current in the AlGaN FPAs.

For each device wafer described in Section 2 a 640 x 512/15 FPA was characterized for a set of eight different photon flux conditions. The transmission wavelength of the monochromator was set to the peak EQE value as determined before on the test devices in each case. As typical example, Figure 9 shows a map of the total pixel current of the FPA fabricated from the device wafer with vertical structure A (continuously graded buffer) for a photon flux nominally attenuated by a factor of 100. Clearly, the percentage of open pixels characterized by a very low current close to the ROIC leakage level ($\approx 2$ fA) is very low. In particular, the virtual absence of large clusters of open pixels shows that the low residual bowing of the diced AlGaN detector arrays allows a successful hybridization with the ROIC. Obviously, pixels with a very high total current are also extremely rare and a very low percentage of pixel outages due to excessive dark current was achieved, despite significant persistent densities of point defects and threading dislocations as evident from $\omega$-scan diffuse scattering as well as the FWHM values. The current mapping of the array does show sort of a four-quadrant-like subdivision. This feature that exists in the characterization data of all characterized FPAs is caused by a deficiency of the homogenization optics and is not related to a nonhomogeneity of the detector array. The cluster defect around position ($\approx 300, \approx 420$) with low current values is caused by an epitaxial defect; the arc-like
structure in the left part of the FPA is due to the inhomogeneity in substrate transparency. For the set \( \times 100 \) attenuation conditions, the total pixel current averaged over the entire array without any masking of defect features amounts to \( 3.7 \times 10^{-14} \) A.

Finally, for all three FPAs Figure 10 shows the flux dependence of the pixel current again averaged over the entire array without defect masking. At high photon flux, all three FPAs show a very linear response behavior. At low flux, the pixel current of all three devices is independent of the flux and, as expected, its level approximately matches the leakage level previously characterized for the bare Si ROIC. The transitions between both regimes occurs around a flux level of \( 10^3 \) photons per pixel when normalized to an integration time of 20 ms, which is typical for MAW applications. Evidently, the sensitivity limit of these AlGaN detector arrays is not determined by the dark current of the AlGaN photodiodes, but first and foremost by the Si-ROIC leakage current. Meaningful differences that relate to the three different growth buffer variants could not be discerned in these characterizations.

4. Conclusions

Photomultiplier-governed MAW systems operating in the solar-blind UV would benefit immensely from an all-solid-state alternative detector solution in the form of AlGaN FPAs. Recent advances in terms of available substrate quality and MOCVD growth allowed us to realize narrow-band, solar-blind, ultralow dark current AlGaN photodiode UV detector arrays with excellent out-of-band suppression ratios and a highly linear response. Remarkably, the sensitivity of the very first generation of AlGaN FPAs was not limited by the dark current of the AlGaN photodiodes. Yet, a not fully optimized device design for maximizing the EQE and, in particular, current leakage paths associated with the Si ROIC were limiting. Both points can be addressed in a straightforward manner. Although the signal-to-noise ratio has not been properly determined so far, the results shown in Figure 10 nourish the expectation that even this first device generation should allow us to discern signal levels of a few hundred photons per pixel per frame when the ROIC-related offset is subtracted. Apart from enhancing the EQE by optimizing the vertical device design use of a thermoelectric cooler or, preferably, the development of a dedicated, specifically designed zero-leakage ROIC could clearly boost the sensitivity much further. Overall, AlGaN FPAs appear to be viable approach for the realization of solar-blind, low size, weight, and power detectors for airborne MAW applications.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

AlGaN, focal plane arrays, solar blind, ultraviolet detection

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