

III-nitride-based Visible-blind and Solar-blind Photodetectors

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2012.9.22

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Outline

- Brief introduction
- MSM APDs based on homoepitaxial GaN
- AlGaN-based solar-blind photodetectors
- AlGaN-based RCE photodetectors
- Summary and acknowledgement

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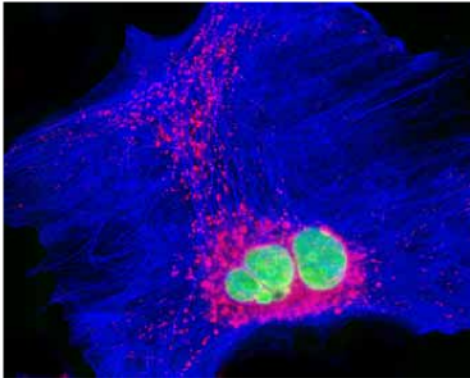


The significant applications of UV photodetectors

UV detectors have important applications in the fields of environmental monitoring, life science, solar physics, electric power industry and defense.



Corona detection



Biological sensing

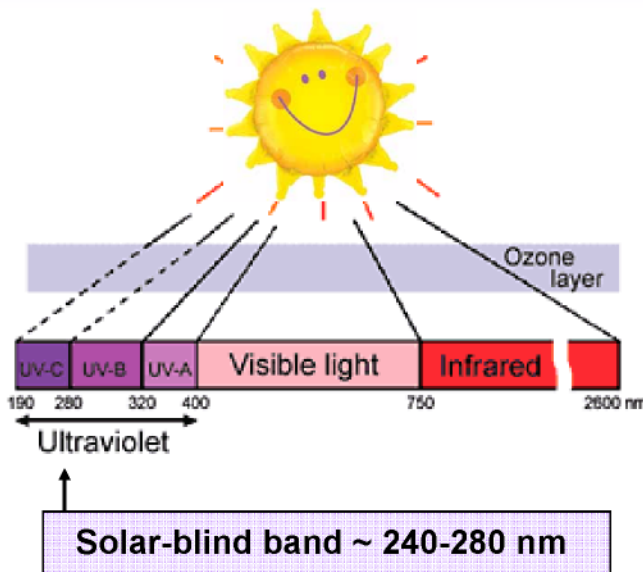


Environmental monitoring

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Photodetectors working in solar-blind UV band



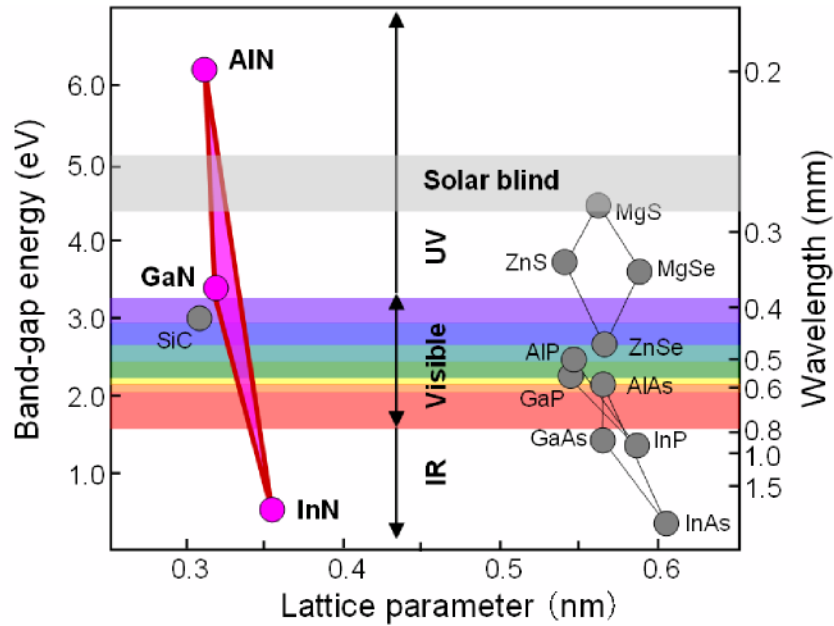
Missile plume detection

Solar radiation in this band is completely absorbed by the ozone layer of the atmosphere and does not reach the earth surface. Detection in this band in full daylight is therefore performed with negligible background and at high signal-to-background noise ratio.

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III-nitrides for UV-detector applications

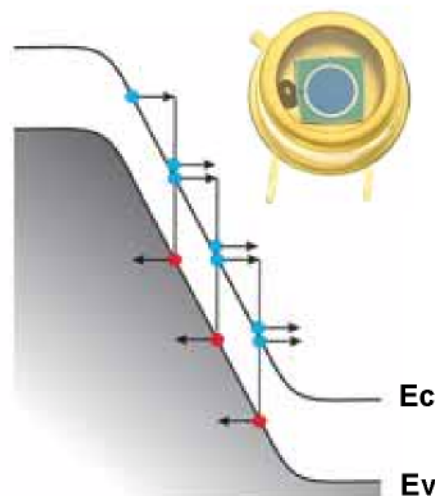


By adjusting its Al-content, the direct bandgap energy of AlGaIn alloy varies from 3.4 to 6.2 eV, covering the conventional UVA/UVB as well as the solar-blind UVC band.

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MSM APDs fabricated on GaN homo-epilayer

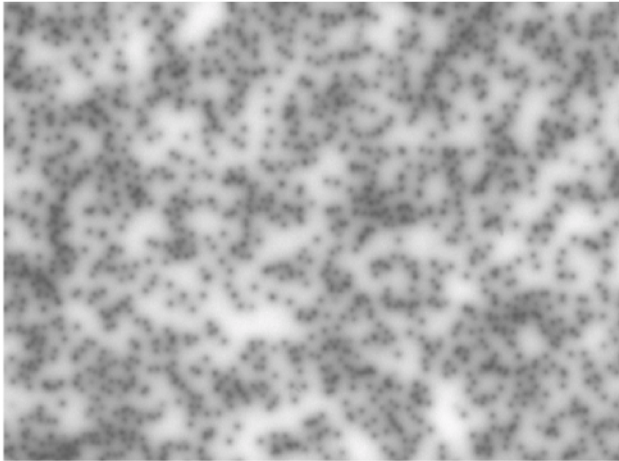


High field operation requires high crystalline quality

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A typical MOCVD GaN film on sapphire



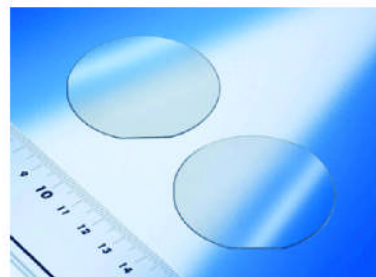
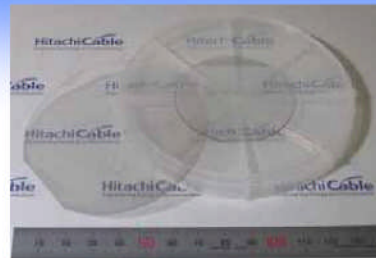
Large lattice mismatch

	$[11-20]_{\text{III-N}} // [10-10]_{\text{Sap}}$ 30° Rotation
Atomic arrangement	
GaN a=3.189 Å	+16.1%

It is well accepted that defects in GaN, especially TDs, are:

- non-radiative recombination centers
- leakage paths
- carrier traps
- and scattering centers

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Sumitomo Electric's bulk GaN



HVPE GaN template (Nanjing Univ.)

Bulk GaN is gradually commercially available, but what we **really** need is high-quality epi-layer.



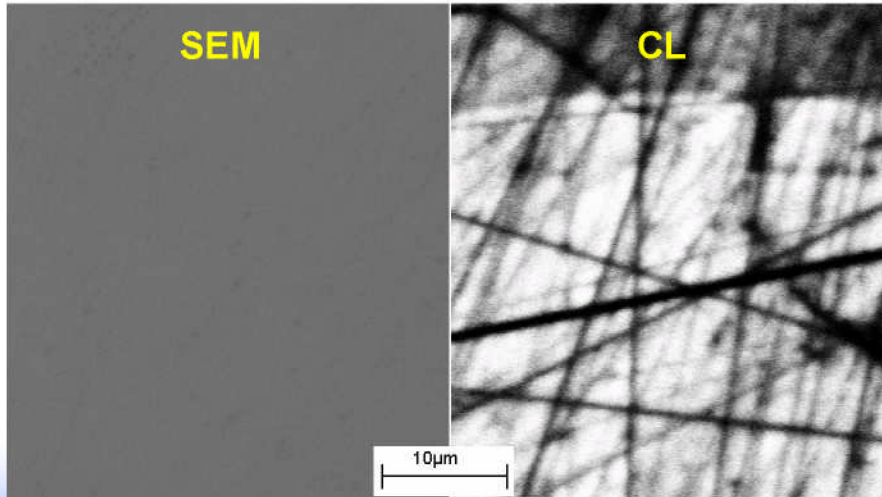
Homoepitaxy

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The problems faced by homo-epi

- Different thermal conductivity
 - Small wafer size normally
- } Need more experience
- The bulk GaN technology is not that mature. The GaN substrate might not be truly epi-ready.



An extreme case:

Severe sub-surface damage revealed by CL, rms roughness \sim 0.5 nm

Solid-state Electronics 52, 817 (2008)

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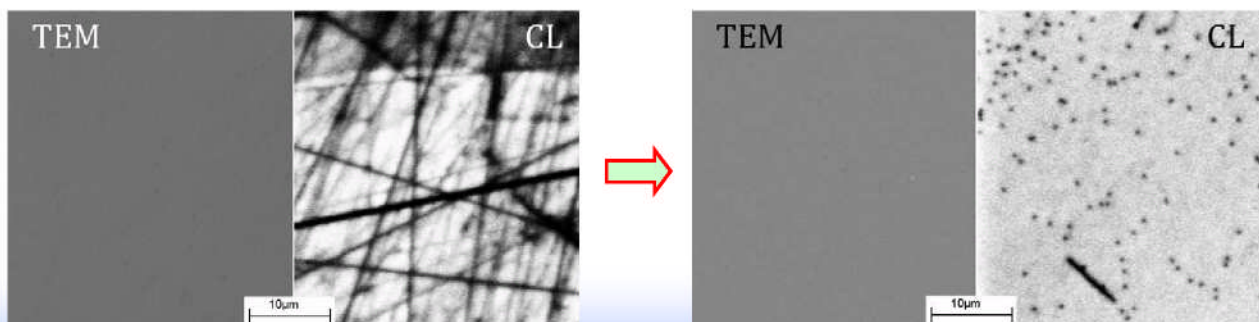


In-situ micro-etching technique

Materials: bulk GaN substrates from several vendors and HVPE GaN template prepared by Nanjing Univ.

Process: annealing the samples in a mixture of NH_3 and H_2 at the high temperature for a certain time period.

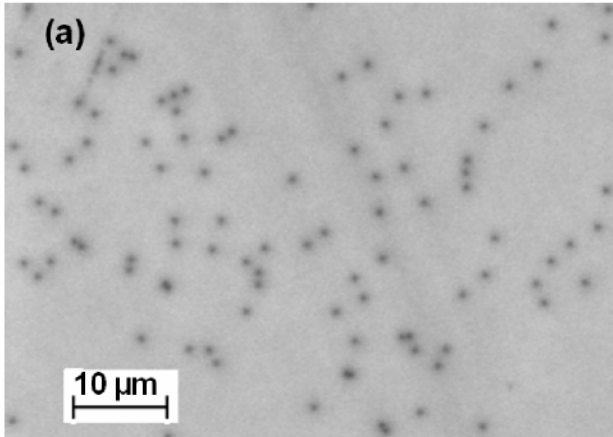
What happens: we believe that the residual surface damages can be reduced by this controlled decomposition process.



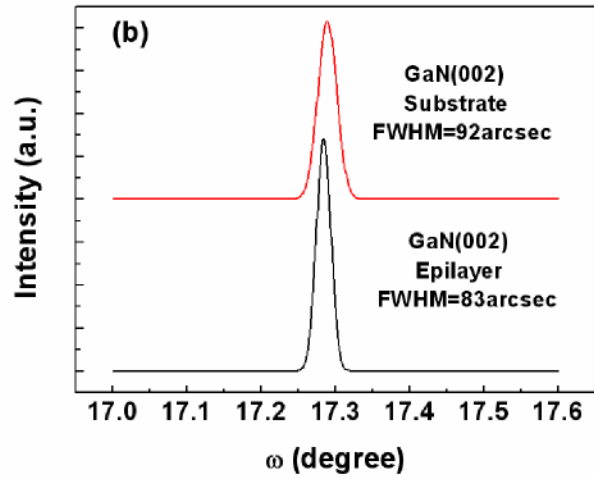
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High crystalline-quality GaN homo-epilayer



DD $\sim 4 \times 10^6 \text{ cm}^{-2}$
GaN substrate dependent



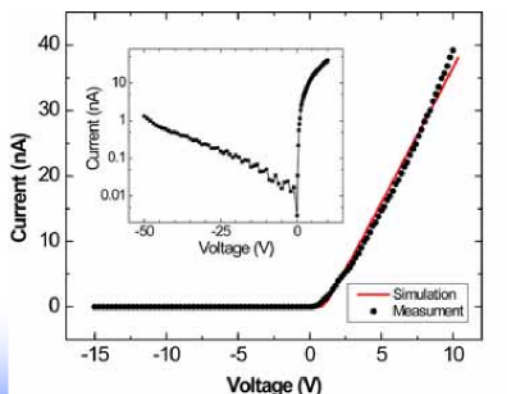
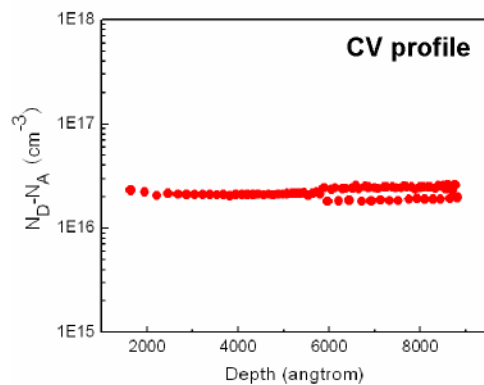
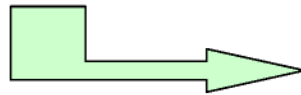
Crystalline-quality is further improved through homo-epi

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Wide-range-control of n-type doping

- High-doping: up to \sim high 10^{19} cm^{-3}
- Low-doping: down to \sim low 10^{16} cm^{-3}
- Semi-insulating:



By using a Schottky-diode-like structure, the RT resistivity is estimated as high as $10^{10} \Omega \text{ cm}$.

Electronics Lett. 45, 910 (2009)

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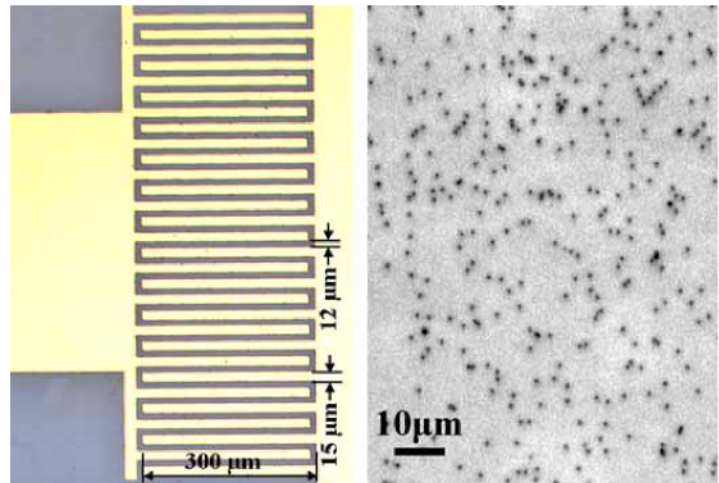


MSM-PDs on GaN homo-epilayer

- MSM PDs have many intrinsic advantages over other types of PDs.
- **Dark current determines weak-signal-detection capability.** But past MSM-PDs fabricated on sapphire usually suffer from high dark current.



MSM-PDs on Bulk GaN

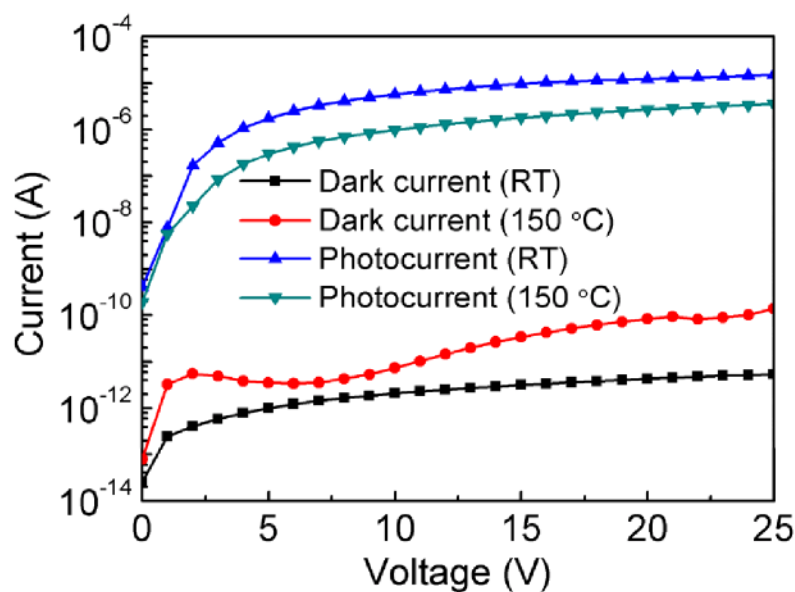


Solid-state Electronics 57, 39 (2011)

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Ultra-low dark current is achieved !

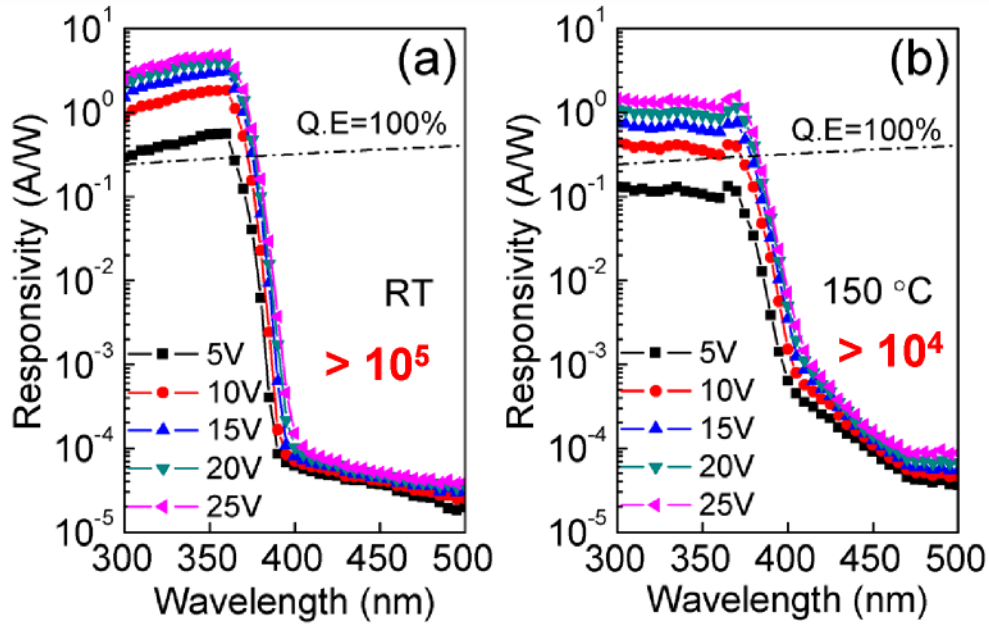


Dark current of the PD is significantly reduced, even at elevated temperatures.

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High UV-to-visible rejection ratio

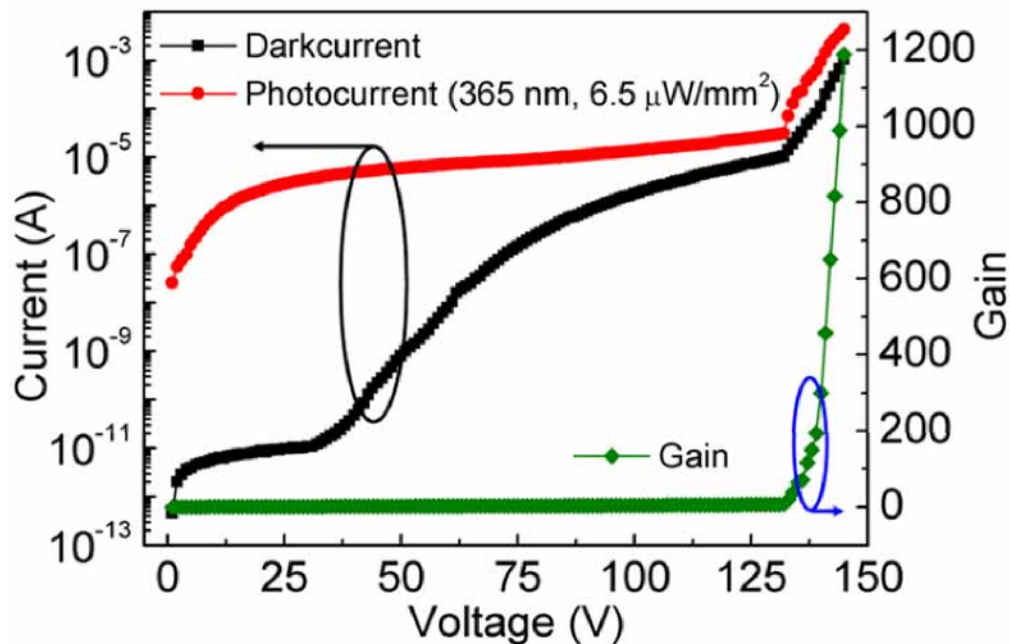


The PD still exhibits an internal gain mechanism, which is attributed to photo-generated holes trapped at the semiconductor/metal interface as well as field-induced image-force lowering effect.

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MSM-APDs on GaN homo-epilayer

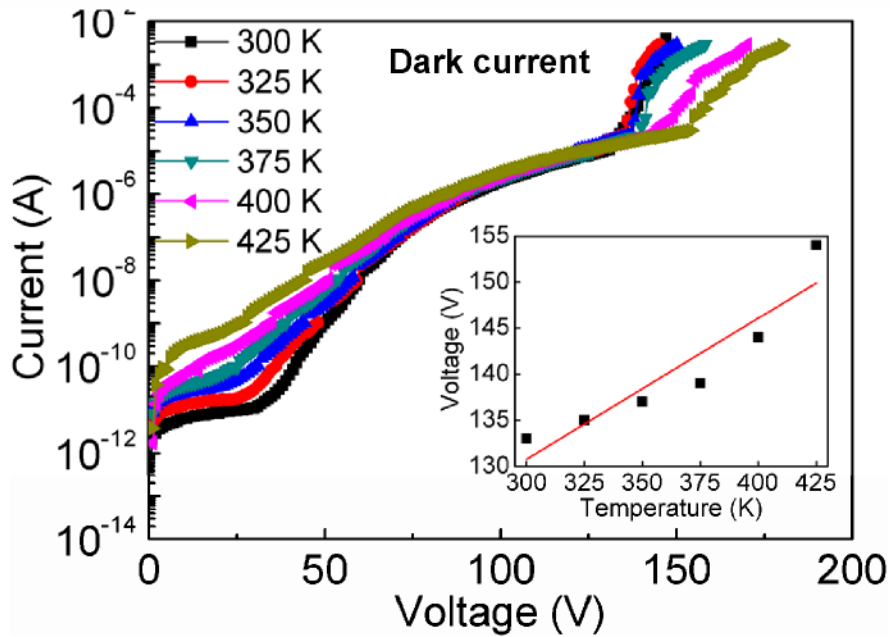


If we further increase bias until the critical electrical field of GaN is reached along the edge of contact electrodes, the MSM PD just introduced could change into an **APD** ! It is the largest GaN APD reported so far.

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Temperature dependent breakdown characteristics



The BVs of the MSM-APD show a positive temperature coefficient of 0.15 V/K, confirming that the gain is dominated by avalanche breakdown mechanism.

IEEE Electron Dev Lett 32, 1260 (2011)

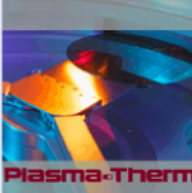
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News

5 August 2011

Metal-nitride semiconductor avalanche for UV detection

Researchers in China have reported the first demonstration of a gallium nitride (GaN)-based planar metal-semiconductor-metal avalanche photodiode (APD) sensitive to ultraviolet light [F. Xie et al, IEEE Electron Device Letters, published online 14 July 2011]. The research group consisted of scientists from Nanjing National Laboratory of Microstructures, the Jiangsu Provincial Key Laboratory of Advanced Photonic and Electronic Materials, and Nanjing University.

The researchers used conductive free-standing bulk GaN substrates created via hydride vapor phase epitaxy (HVPE) to improve material quality. These substrates are much more expensive than the sapphire substrates used commercially as a base for nitride growth. However, as techniques develop it is to be hoped that free-standing GaN will drop in price. By using such substrates, the researchers were able to make devices with $400\mu\text{m} \times 400\mu\text{m}$ effective device area, which is claimed to be the largest for GaN-based APDs so far reported.

Avalanche photodiodes work in a reverse-bias state, where a photon that is absorbed produces an electron-hole pair, the electron of which then accelerates in the high bias field and goes on to create further electrons by impact ionization. Gallium nitride has a wide bandgap of about 3.4eV that makes it sensitive to ultraviolet light with wavelengths greater than 365nm.

It is important in such devices that dark current and premature breakdown microplasma effects be reduced. As usual, these problems in nitrides are linked to material quality. The most commercial technique at present for producing nitride semiconductor devices is to grow the material on sapphire substrates. However, such growth results in many dislocations and other defects. The presence of defects restricts the area of devices that can be achieved, usually to less than 100µm in diameter.

The free-standing substrates used for the Chinese research were 320µm thick and had a room-temperature conductivity of $\sim 0.01\Omega\text{-cm}$. Metal-organic chemical vapor deposition (MOCVD) homoepitaxy added a 1µm heavily n-type GaN buffer layer, followed by a 3µm n-type GaN active layer.

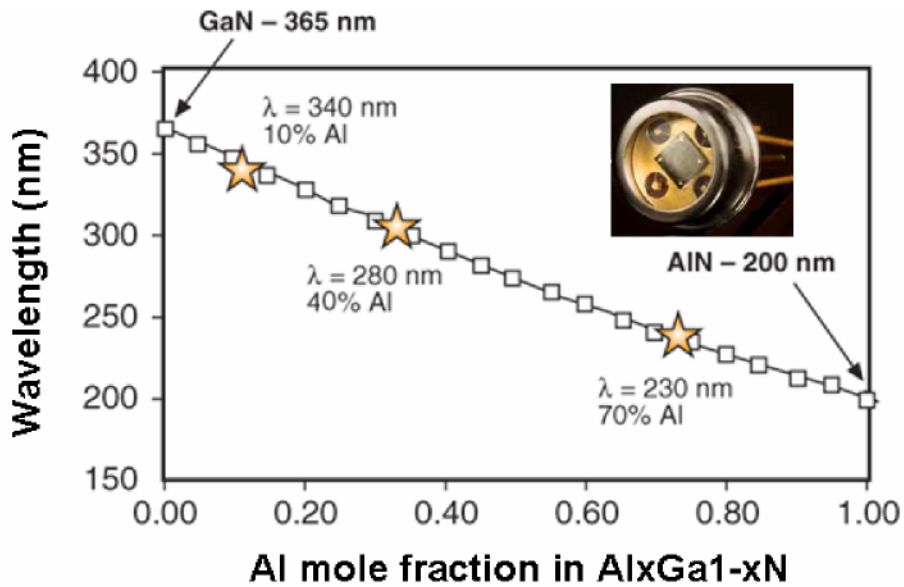
The dislocation density in the GaN layer was measured via cathodoluminescence



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AlGaN-based solar-blind photodetectors



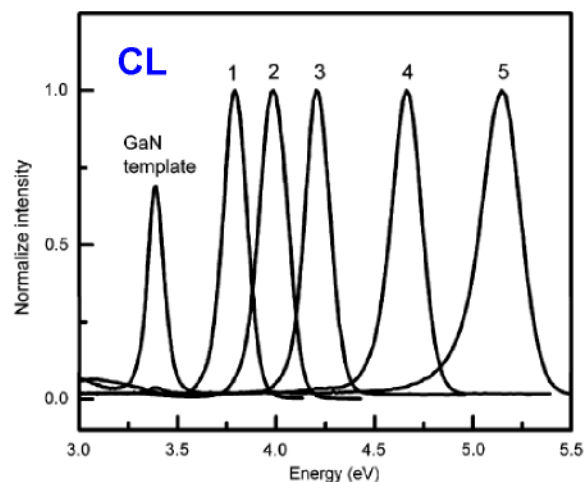
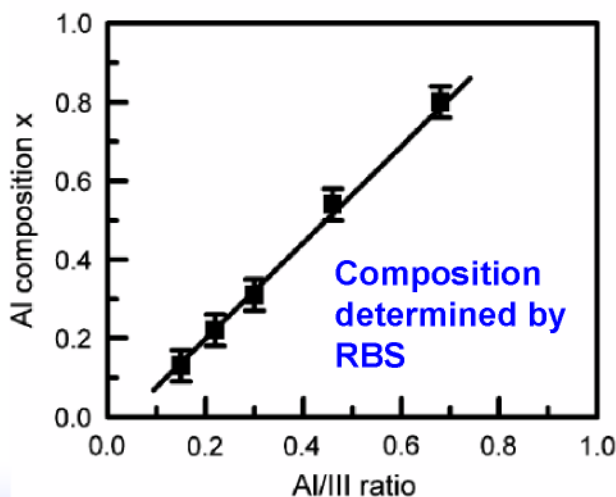
The biggest challenge lies in the material growth !

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MOCVD growth of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ ($0 \leq x \leq 1$)

- Approximate III/V ratio
- Higher growth temperature
- High temperature AlN buffer
- AlGaN/AlN superlattice dislocation-filtering layer

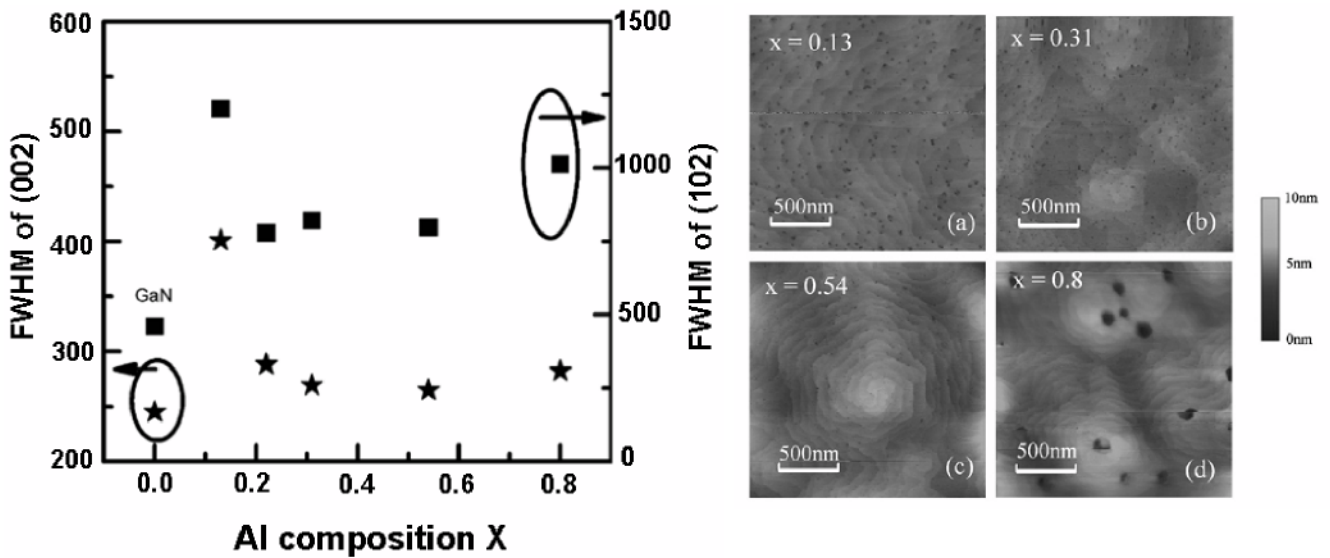


Full composition range can be covered.

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Basic material characterizations



- The FWHMs of (002) rocking curves are commonly below 300 arcsec.
- Clear atomic steps can be observed for most Al compositions indicating smooth surface morphology.

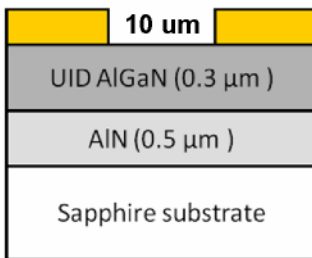
J. Cryst Growth 310, 4499 (2008)

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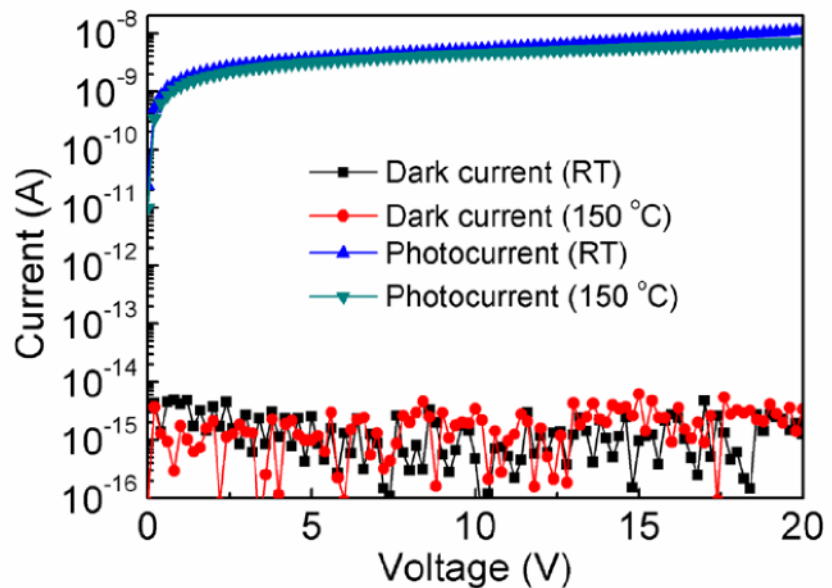


1. Small-size ($400 \times 400 \mu\text{m}^2$) AlGaIn MSM solar-blind photodetector

Semi-trans Ni/Au (5/5nm)



$400 \times 400 \mu\text{m}^2$



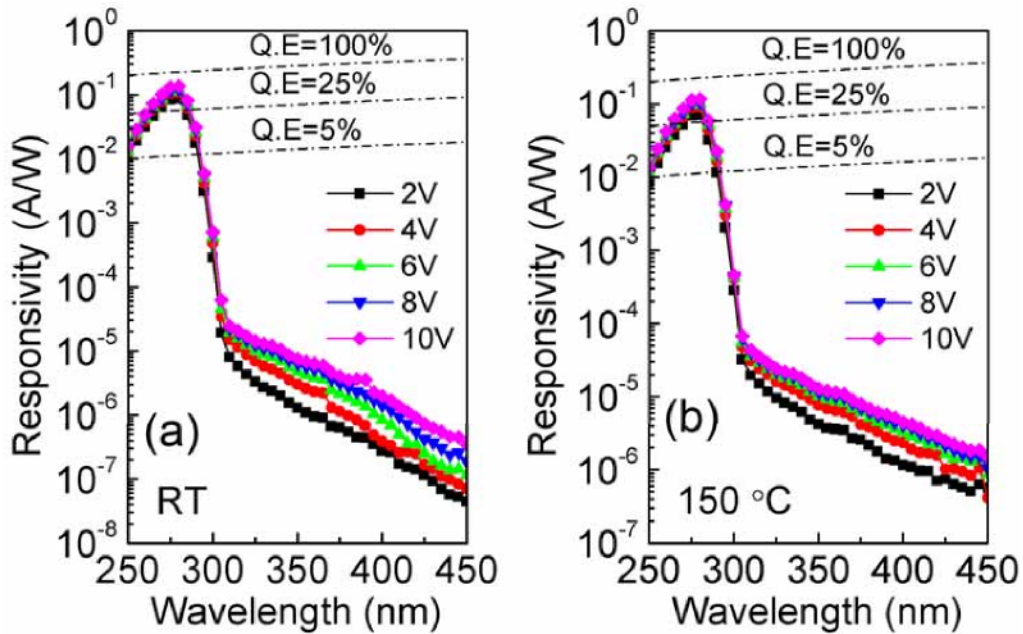
By developing a special **surface passivation** technique, record-low dark current is achieved !

IEEE Sensor J. 12, 2086 (2012)

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Remarkable photo-response characteristics for harsh environmental applications



- RT, 10V bias: Max QE~64%, Rejection ratio (275/350nm) $>1.8 \times 10^4$
- 150°C, 10V bias: Max QE~51%, Rejection ratio (275/350nm) $>8 \times 10^3$

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News
 29 May 2012
High-temperature solar-blind AlGaN photodetectors
 Researchers in Nanjing, China have reported the first fabrication and characterization of high-temperature solar-blind photodetectors (PDs) based on an aluminum gallium nitride (AlGaN) absorption layer and planar metal-semiconductor-metal (MSM) electrode layout. (Feng Jie et al., IEEE Sensors Journal, vol. 12, p.2095, June 2012). The participating institutions were Jiangsu Provincial Key Laboratory of Advanced Photonic and Electronic Materials/Nanjing University and Nanjing Electron Devices Institute.

The new devices have an ultra-low dark current in the femtoamp ($I_A = 10^{-15}$ A) range, even at 150° C. At room temperature (RT), the solar-blind/ultraviolet rejection ratio is four orders of magnitude, and even at 150° C its value is more than 1000. The researchers comment on their device: "The ultra-... at 150° C suggest that such PDs are suitable for high-...

...ile plume sensing, flame detection, environmental action, and covert space-to-space communications. ... using fragile photomultiplier tubes or silicon expensive fibers, and bulky high-voltage power supplies, items can be sensitive to harsh environments such as that...

...ally solar blind due to its large bandgap. The wide in-temperature operation. Radiation hardness is another...

...as grown on 2-inch sapphire substrate using metal-... (C). The 1100° C AlGaN layer was not intentionally dop... s confirmed by a 33.3nm cut-off in optical transmission... sd to be highly resistive, and was grown according to the re recipe.

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Solar-Blind AlGaN Photodetectors With Record-Low Dark Current
 June 14, 2012

Aluminum gallium nitride photodetectors have been fabricated by Chinese researchers using a proprietary high-temperature MOCVD process and a special surface treatment.

A collaboration between researchers from Nanjing University and Nanjing Electron Devices Institute, China has developed a high quantum efficiency AlGaN-based solar-blind photodetector with a very low dark current.

Despite their significant applications including missile plume sensing, environmental monitoring, chemical/biological agent detection, and solar physics, AlGaN-based solar-blind photodetectors commonly suffer from low quantum efficiency and a high dark current. This significantly limits their weak signal detection capability.

But for use in harsh environments, such as flame detection for gas turbines or in complex battle field applications, photodetectors capable of operating at high temperature are very much needed.

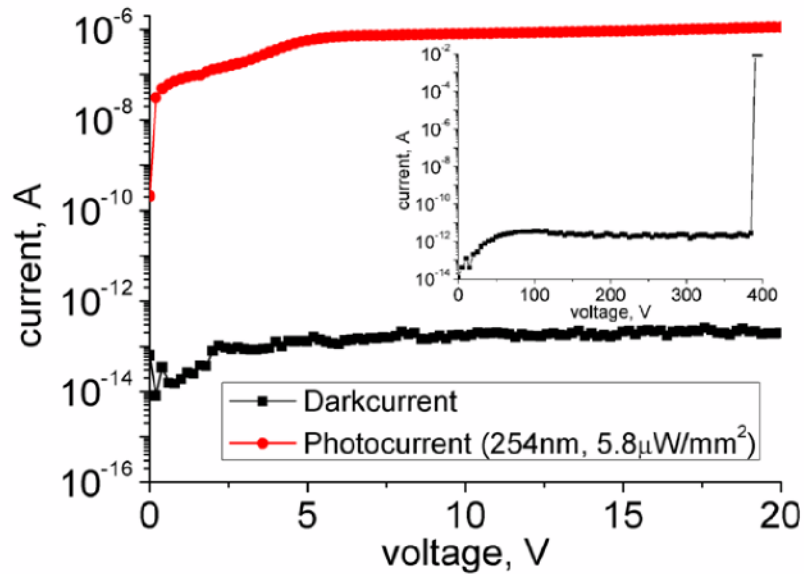
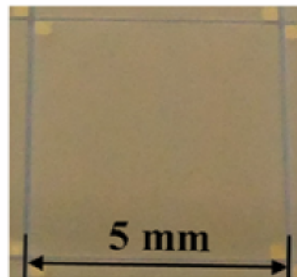
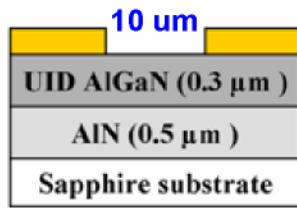
To address this problem, the research team, led by Hai Lu, a professor at Nanjing University, has fabricated a novel AlGaN-based solar-blind MSM photodetector. Using a proprietary high-temperature epitaxial growth process and a special surface treatment technique, they have created a device that they say has a record low dark current - not only at room temperature, but also at elevated temperatures.

The photodiode structure, grown on sapphire by MOCVD, consists of a high-temperature AlN buffer layer and an undoped Al_{0.4}Ga_{0.6}N active layer. Standard optical lithography and lift-off techniques have been used to define the Ni/Au semi-transparent interdigitated contact electrodes. Before the deposition of the Schottky metal by e-beam evaporation, a special surface chemical treatment was conducted.

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2. Large-size ($5 \times 5 \text{ mm}^2$) AlGaN MSM solar-blind photodetector

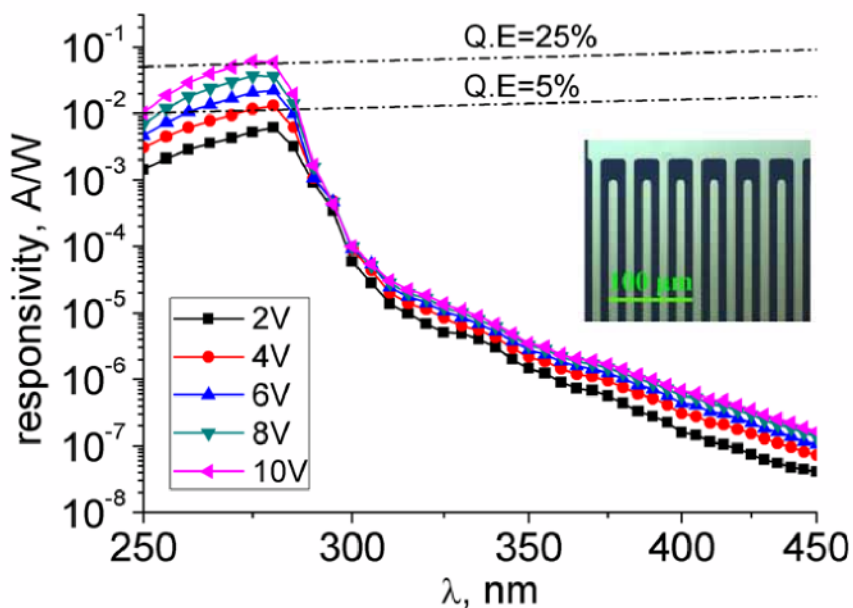


- Largest-area AlGaN PD reported so far
- Record-low dark current density ($3.2 \times 10^{-12} \text{ A}/\text{cm}^2$, 20 V)

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Photo-response characteristics of the large-area PDs



RT, Max QE~28% (10V bias), Rejection ratio (275/350nm) $> 1 \times 10^4$, suggesting good material uniformity.

Electronics Lett. 47, 930 (2011)

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In brief - Seeing blind

Published on 3 August 2011

You are here: Knowledge Network home > Magazines > Electronics Letters - features > vol 47 issue 16



The device has low area and the lowest dark-current density.

Toolbox

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Large-area solar-blind AlGaIn-based MSM photodetectors with ultra-low dark current
Electron. Lett. -- 4 August 2011 -- Volume 47, Issue 16, p.930 - 931

F. Xie (1), H. Lu (1), D.J. Chen (1), P. Han (1), R. Zhang (1), Y.D. Zheng (1), L. Li (2), W.H. Jiang (2) and C. Chen (2)

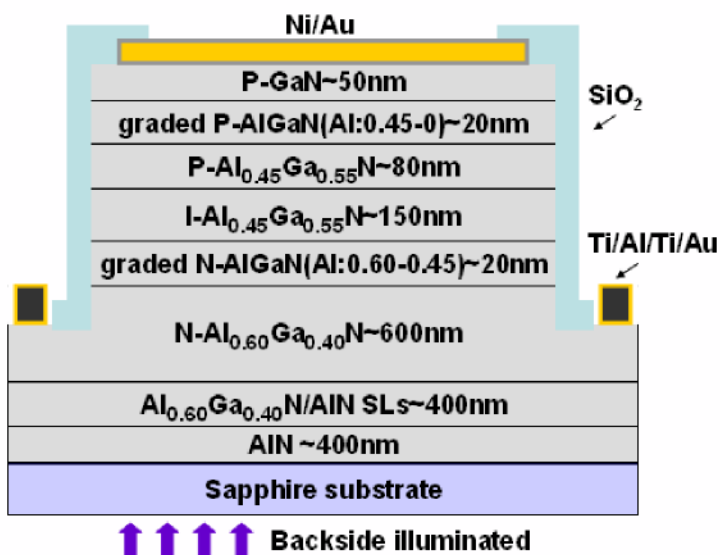
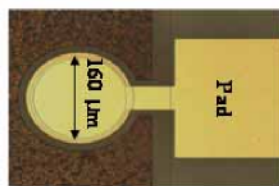
(1) Nanjing University, Jiangsu Provincial Key Laboratory of Advanced Photonic and Electronic Materials, and School of Electronic Science and Engineering, Nanjing, People's Republic of China

(2) Nanjing Electron Devices Institute, National Key Laboratory of Monolithic Circuits and Modules, Nanjing, People's Republic of China

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3. Back-illuminated AlGaIn PIN solar-blind photodetector

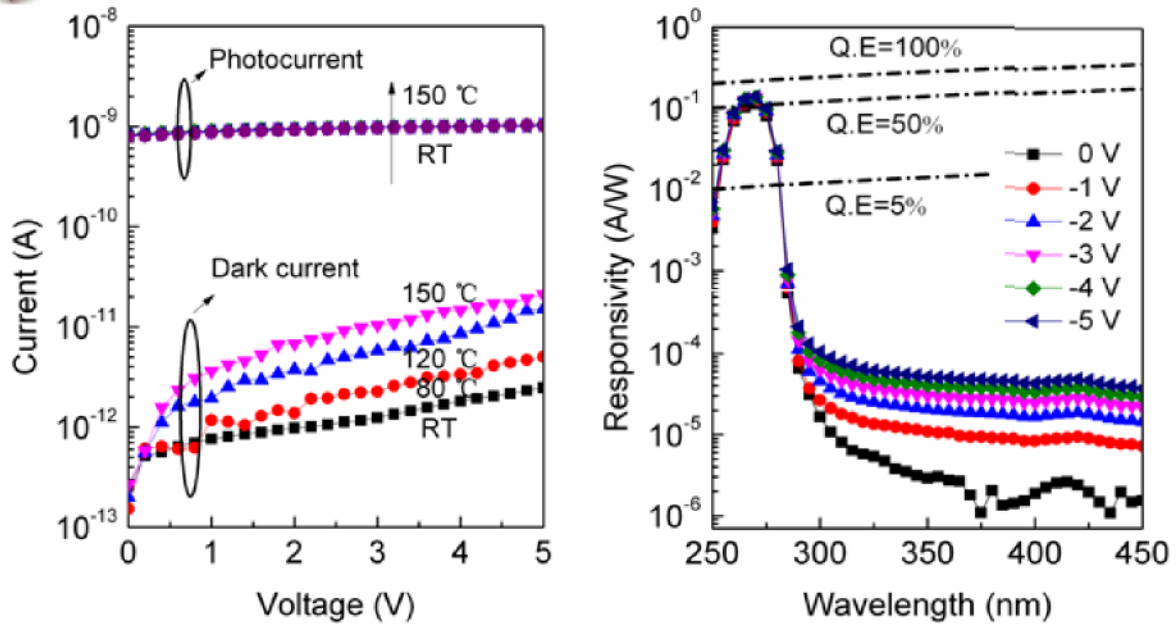


- PIN-type PD has larger fill factor and is capable of PV-mode operation.
- **Epi considerations:**
 - (1) AlGaIn window layer for back-illumination operation;
 - (2) AlGaIn/AlN short-SLs for strain relief and dislocation filtering;
 - (3) Several composition-gradient layers for easy carrier collection;
 - (4) P-GaN cap layer for p-ohmic contact.

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High quantum efficiency photo-response



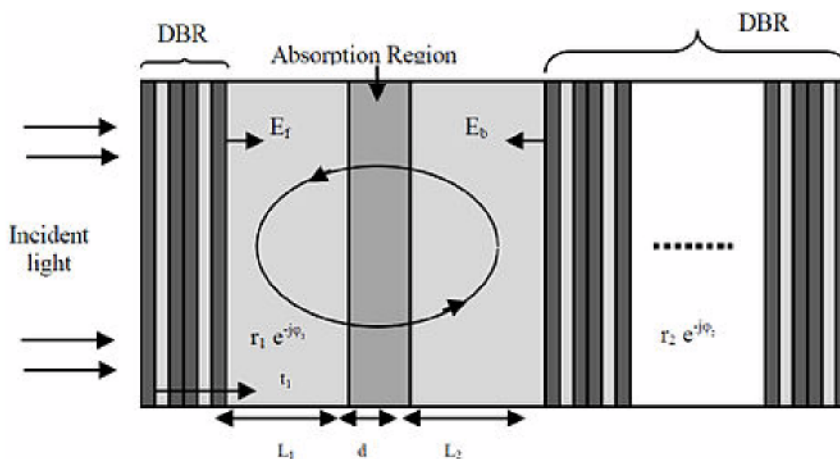
- Low RT dark current and stable photo-current at high temperature;
- Under 0V bias (PV mode), max QE~52%, rejection ratio~ 10^5 ;
- Under 5V bias (PC mode), max QE~64%, rejection ratio $>10^3$.

CPL 29, 097302 (2012)

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AlGaN-based resonant-cavity-enhanced (RCE) photodetectors

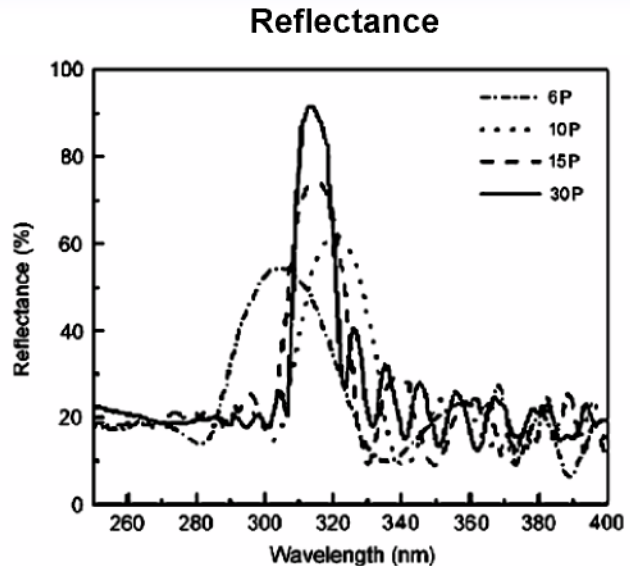
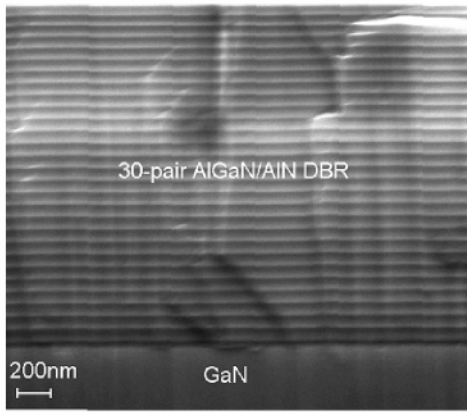
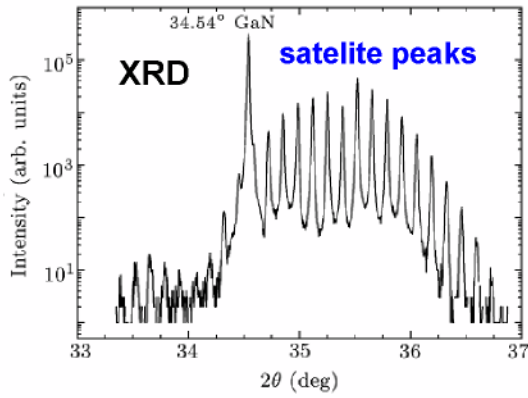


Advantages: wavelength selectivity, narrow spectral width, high speed, and high quantum efficiency (QE)

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High-Al-content AlGaN/AlN DBR structure growth



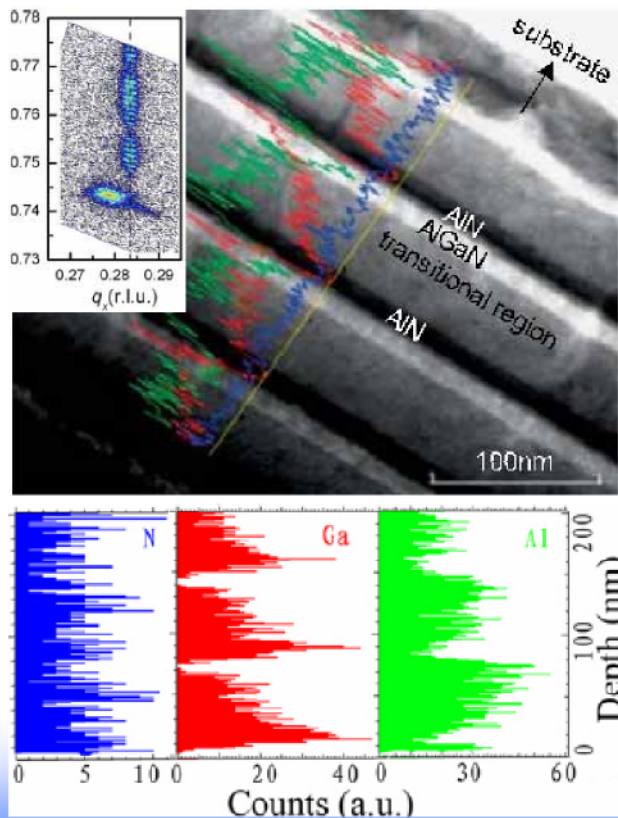
At 320 nm, the max reflectance of the AlN/Al_{0.3}Ga_{0.7}N DBR (30 periods) is ~93.5%.

J. Cryst Growth 298, 357 (2007)

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Compositional pulling effect in the AlGaN/AlN DBRs



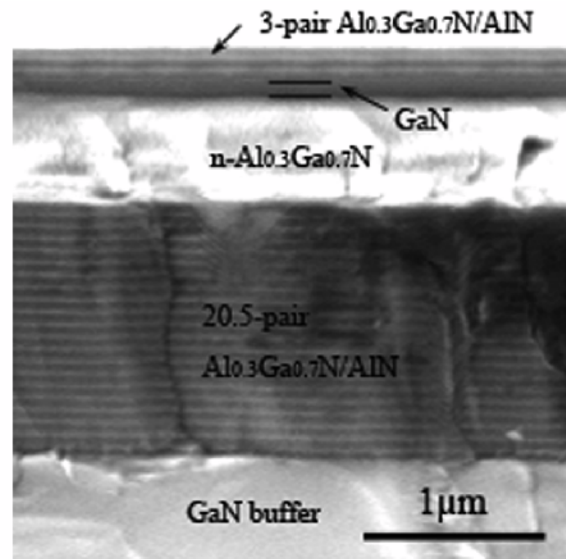
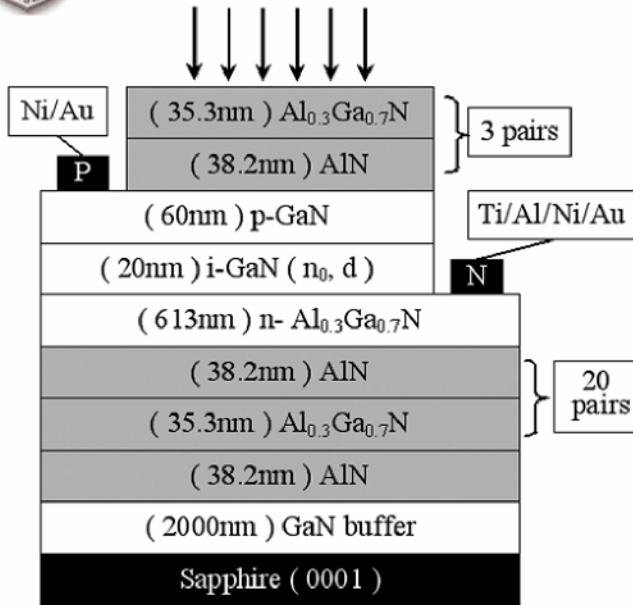
- The reciprocal space mapping contours reveal that these DBRs are coherently grown.
- An AlGaN layer with gradient Al composition is located between the Al_{0.4}Ga_{0.6}N and AlN layers along the [0001] direction. It is attributed to the fact that Ga atoms in AlGaN are pulled and segregated to the upper layer by the strain.

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AlGaN-based RCE photodetectors



A 20.5-pair $\text{AlN}/\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ DBR is used as the back mirror and a 3-pair $\text{AlN}/\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ DBR as the front one. In the cavity is a p-GaN/i-GaN/n- $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ pin structure.

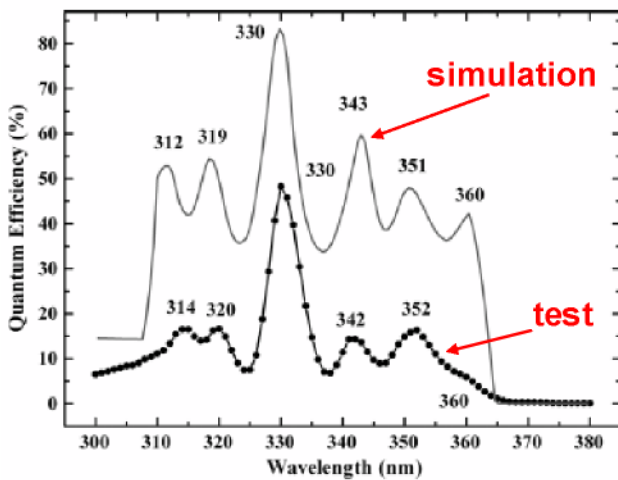
IEEE J. Quantum Electronics, 45, 575 (2009)

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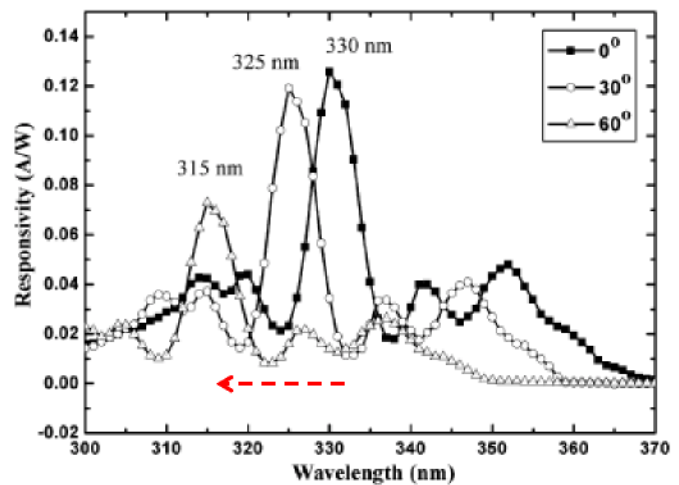


Photo-response of the RCE photodetectors

Selective wavelength response



Incident angle dependence



A response peak of 0.128 A/W at 330 nm with a FWHM of 5.5 nm is obtained under zero bias. Under different incident angles, a significant wavelength shift is obtained, which suggested a convenient wavelength tuning method by controlling the incident angle.

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Summary

1. Wide bandgap III-nitride semiconductors are very attractive for UV photodetector applications due to their wide tunable direct bandgap, and other superior physical properties.
2. Material growth is critical and still challenging for improving the overall device performance, especially for APD applications.
3. Several proto-type PDs working on visible-blind and solar-blind wavelength regions are demonstrated successfully:

GaN MSM APDs on bulk GaN (early stage)

AlGaIn-based solar-blind MSM and PIN PDs
(ready for transition to practical applications)

AlGaIn RCE PDs (early stage)

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Thank you



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