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SAND2019-7691C

Visible and Solar-Blind Photodetectors Using AlGaN High Electron Mobility Transistors with Nanodot-Based Floating Gate

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Goals and Outline

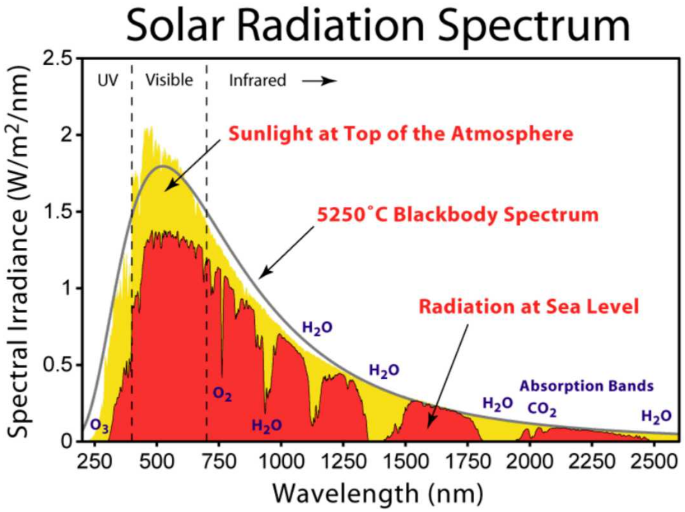
Goal:

- **Demonstrate UV photodetection for AlGaN HEMTs with a nanodot-modulated gate**

Requirements:

- **Must be insensitive to visible light → Reject > 375 nm**
- **Sensitive to UV light**

- ➢ Needs for UV photodetection
- ➢ AlGaN quantum dot floating gate HEMT vis-blind photodetectors
- ➢ Impact of quantum dot placement
- ➢ Extension to solar-blind detection
- ➢ Summary



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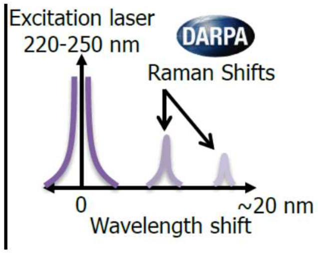
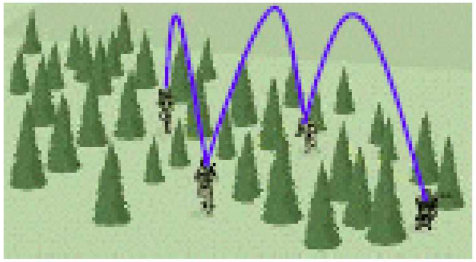
Motivation: Towards portable, highly sensitive UV photodetectors

Raman Spectroscopy
(biological agents)

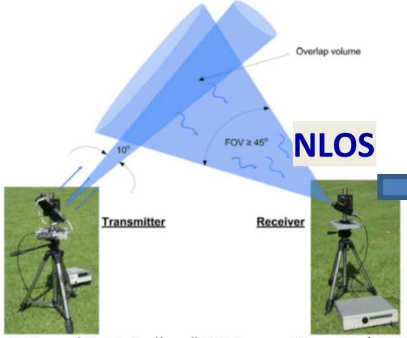


Non-line of sight communication
(covert radio)

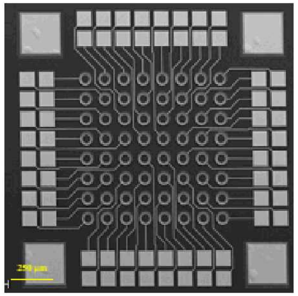


Solar-blind detection
(missile launch, sniper fire)

Benchtop → **Man-portable** → **Micro-opto-electronic**



Z. Xu and B. M. Sadler, "IEEE Comm. Mag. 46, (2008).

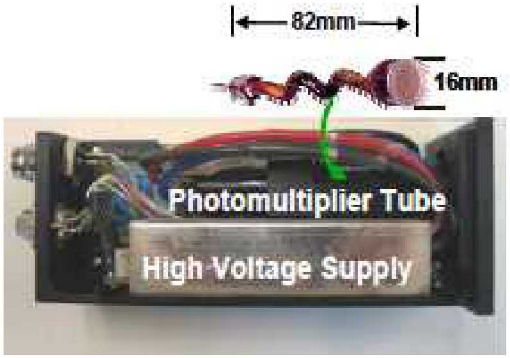


➢ Miniaturization and efficiency are technology drivers

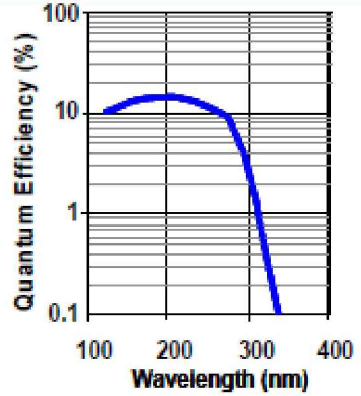
COTS Parts Performance Gap

Photomultiplier Tubes (PMTs)

Large & High Voltage



Low Solar-blind Rejection Ratio



Si Geiger-mode Avalanche Photodiodes (APDs)

Parameter	Hamamatsu S10362-11 Series Device Suffix			
	-025C	-050C	-100C	
Physical area	1x1	1x1	1x1	mm
Number pixels	40x40	20x20	10x10	
Pixel size	25	50	100	µm
Fill factor	30.8	61.5	78.5	%
SPDE at 400nm	25	50	65	%
SPDE at 270nm	8	12	20	%

Cryogenic

Low η

Expensive optical filters

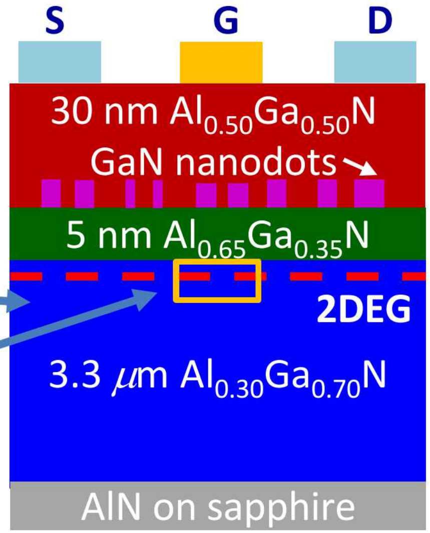
Dead time during reset

Shaw *et al.*, Proc SPIE 7320 1 2009

AlGaN Nano-Dot Floating Gate HEMT Concept

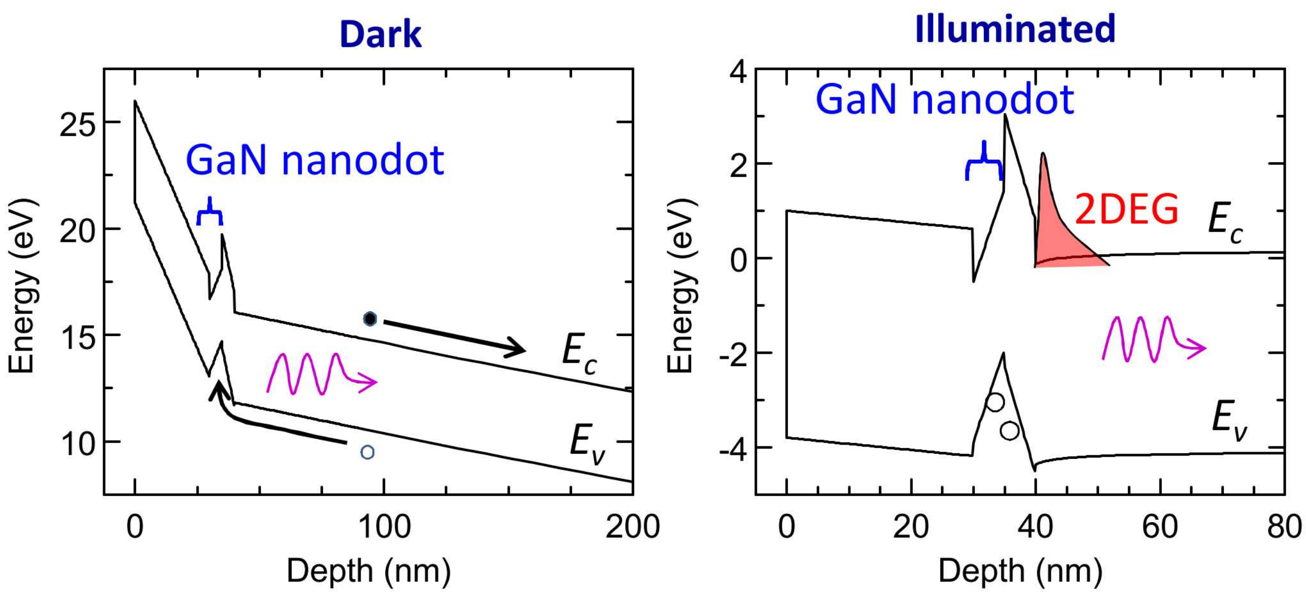
Vis-blind AlGaN QD-FG HEMT

Channel E_{gap} sets absorption wavelength



2DEG under gate modulated by charges occupying nanodots

Energy Band Diagram



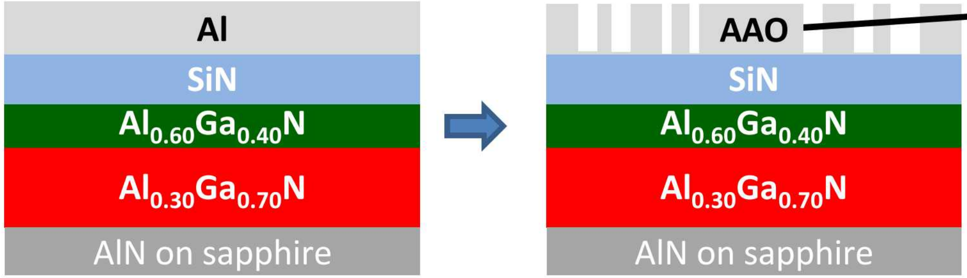
AlGaN quantum dot floating gate HEMT[1]

Locally trap charge carriers in GaN nanodots under illumination, modulating the transistor relative to dark state.

- Small (low voltage)
- Room temperature (large ΔE_V)
- Filter-free (large E_g)
- High sensitivity (Large ΔI_{DS})

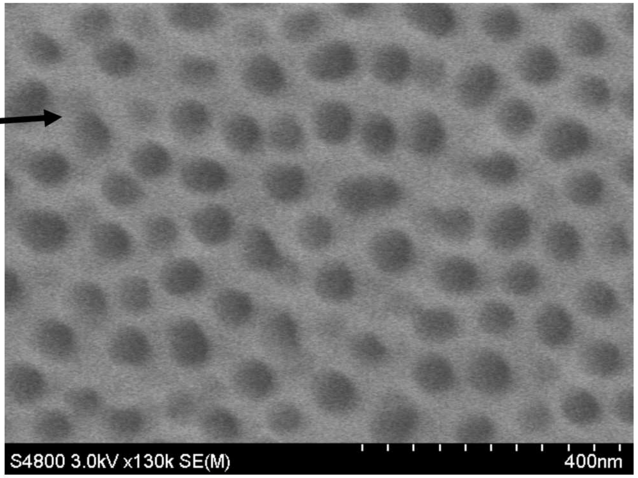
1. Gansen *et al.*, IEEE JSTQE 13, 967 (2007).

GaN Nanodot patterning and growth



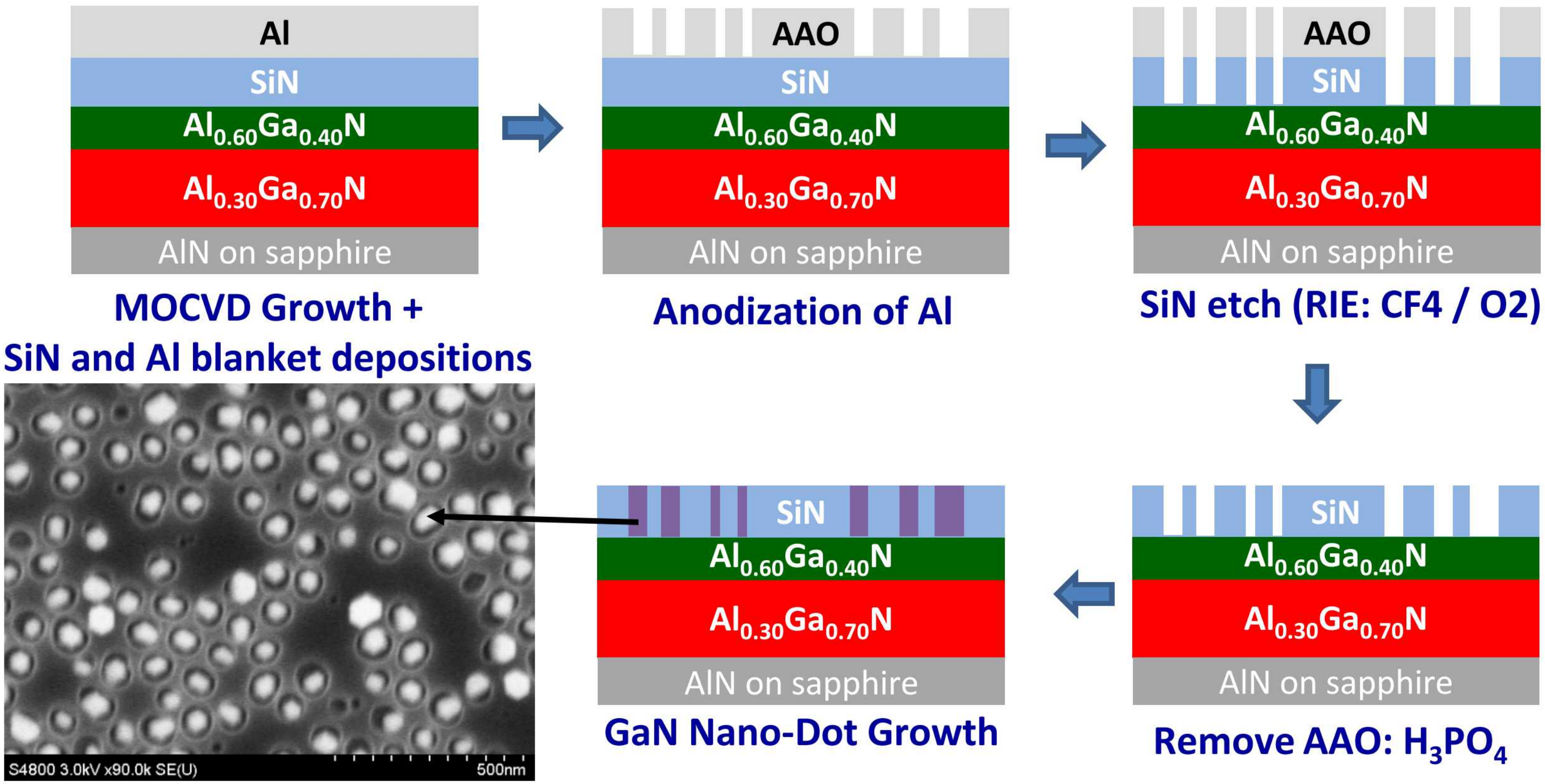
MOCVD Growth + SiN and Al blanket depositions

Anodization of Al



SEM: Anodized Aluminum Oxide

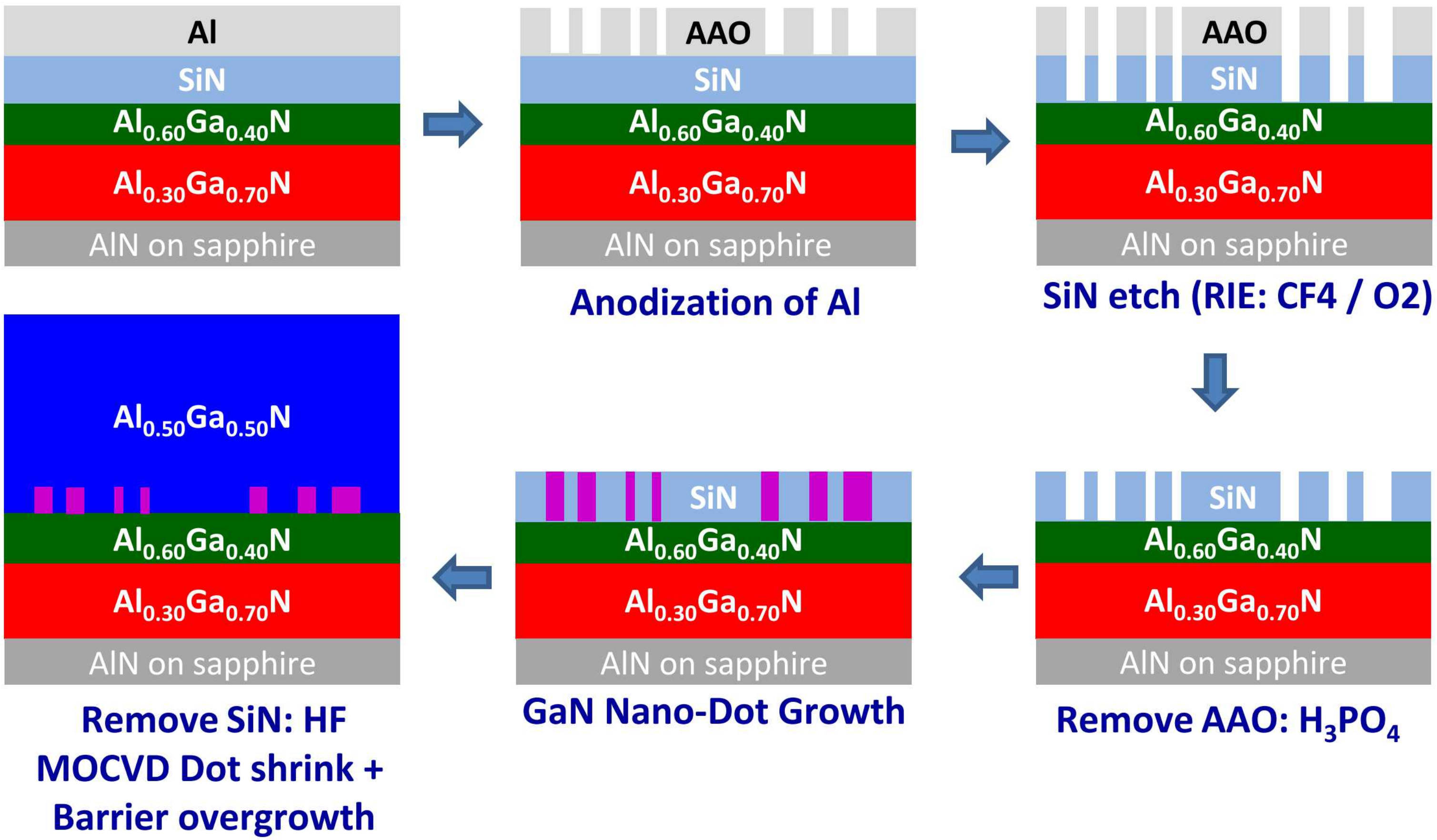
GaN Nanodot patterning and growth



SEM: GaN nano-dots in SiN growth mask

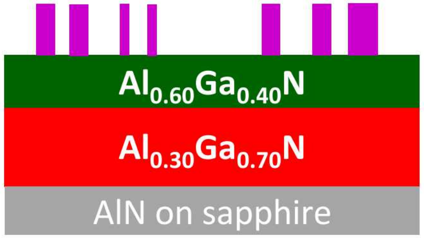
- As-grown GaN nanodots ~ 50 nm in diameter and ~ 50 nm tall
- ~ 10^{10} cm^{-2} nanodot areal density

GaN Nanodot patterning and growth

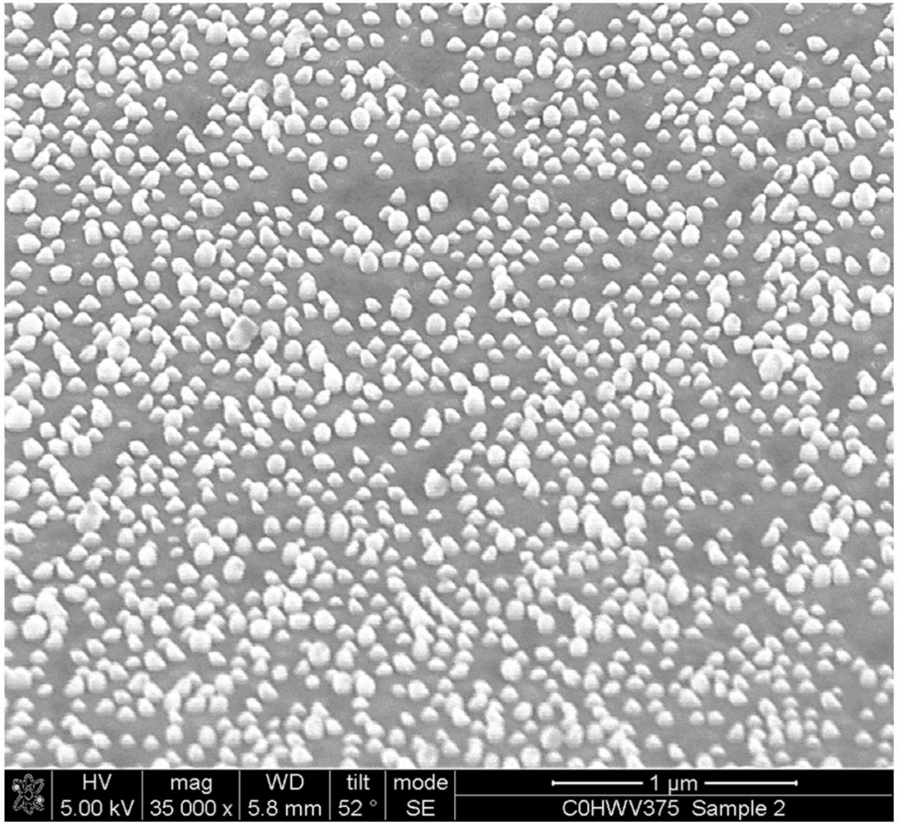


- *In-situ* thermal desorption reduces GaN nanodots to ~ 25 nm and diameter height
- Barrier then grown over the GaN nanodots

GaN nanodot characterization

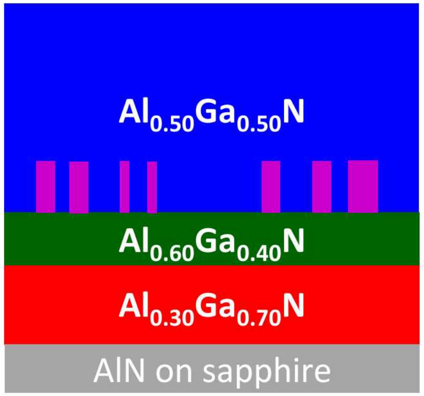


Tilted SEM of GaN nanodots (not shrunk)

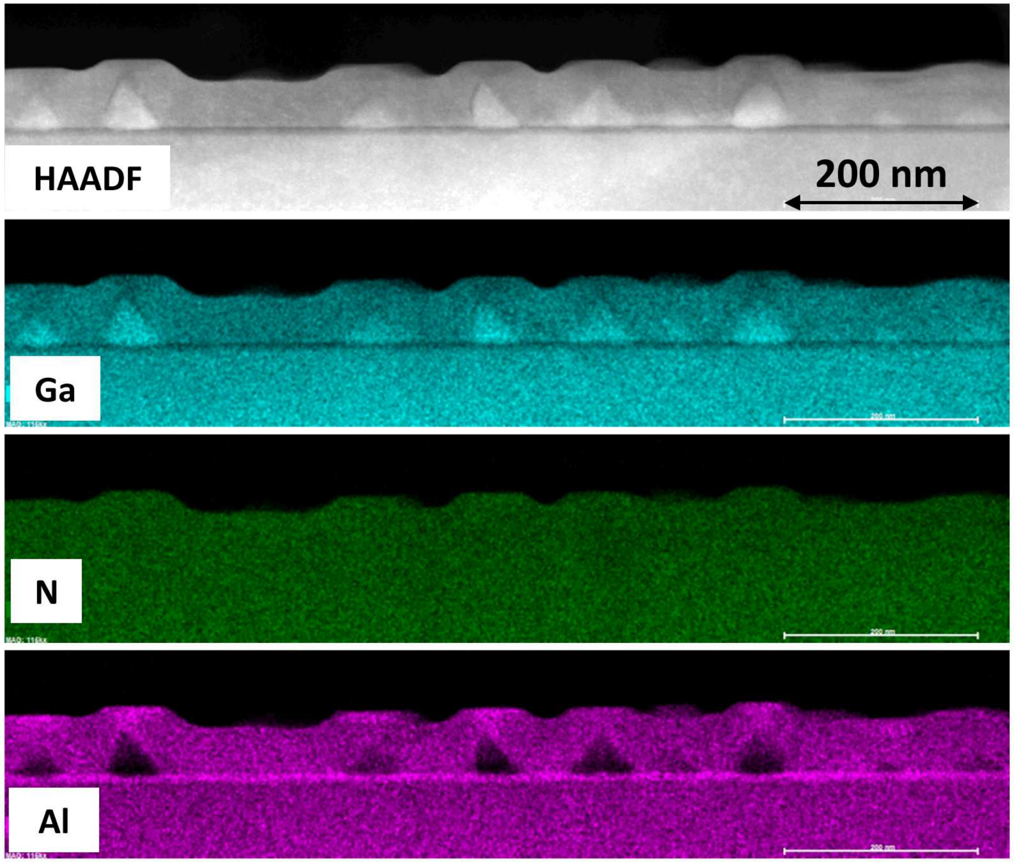


- GaN ~~quantum~~ nanodots ~ 50 nm in diameter and ~ 50 nm tall
- ~ 10^{10} cm^{-2} nanodot areal density
- Nanodot size distribution is not important for this application

GaN nanodot characterization

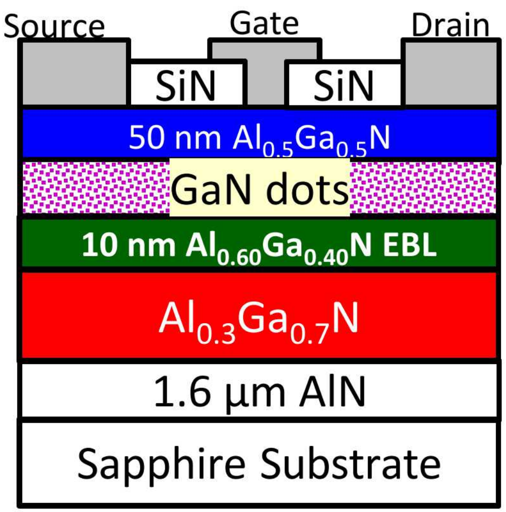


TEM and EDS of embedded GaN nanodots (not shrunk)

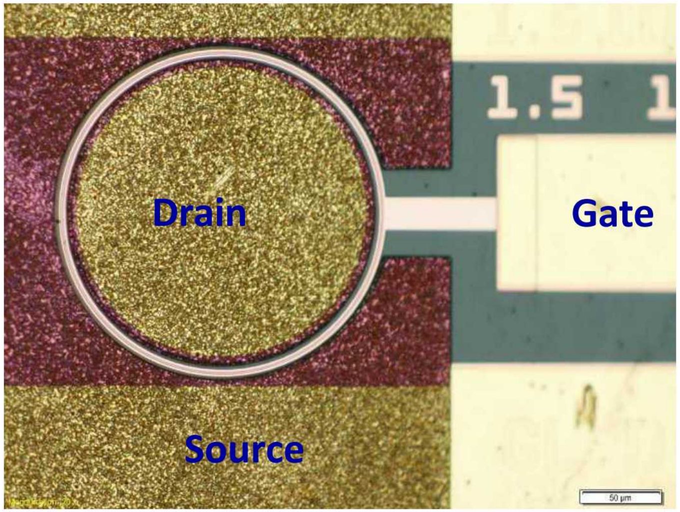


- No evidence of Al uptake during barrier overgrowth

Device fabrication and geometry



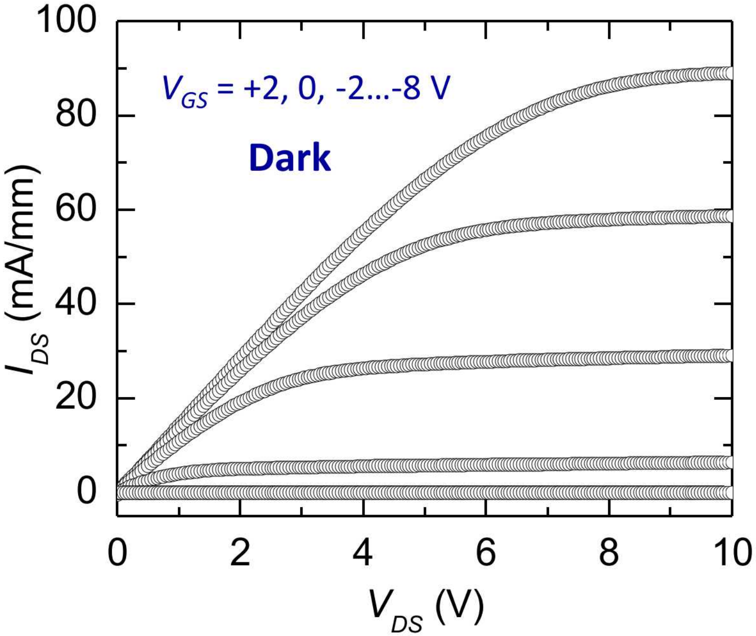
200 µm	Drain Diameter
10 µm	Drain-to-Source
1 µm	Field Plate
1.5 – 3 µm	Gate Length



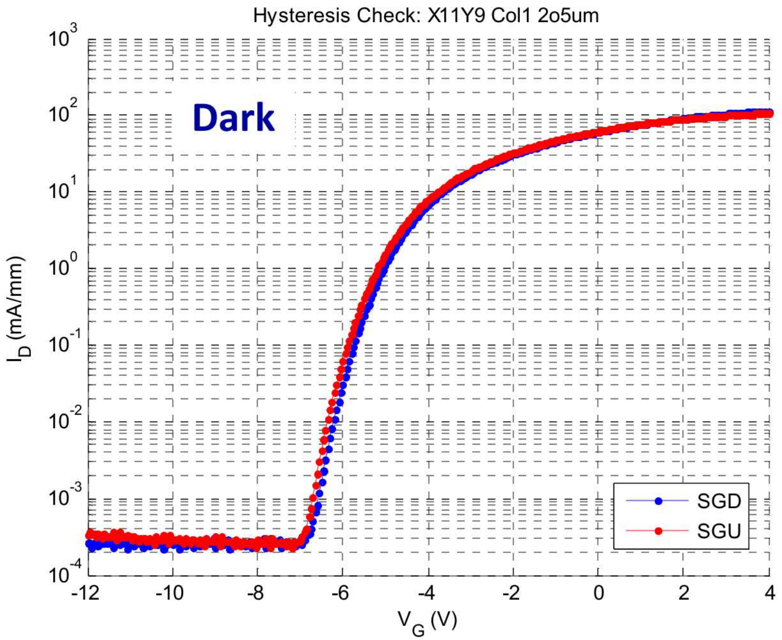
- 8 nm semi-transparent Ni gate
- Ti/Al/Ni/Au ohmics annealed at 900° C

AlGaN Nanodot HEMT with good electrical characteristics

I-V of nanodot 50/30 HEMT

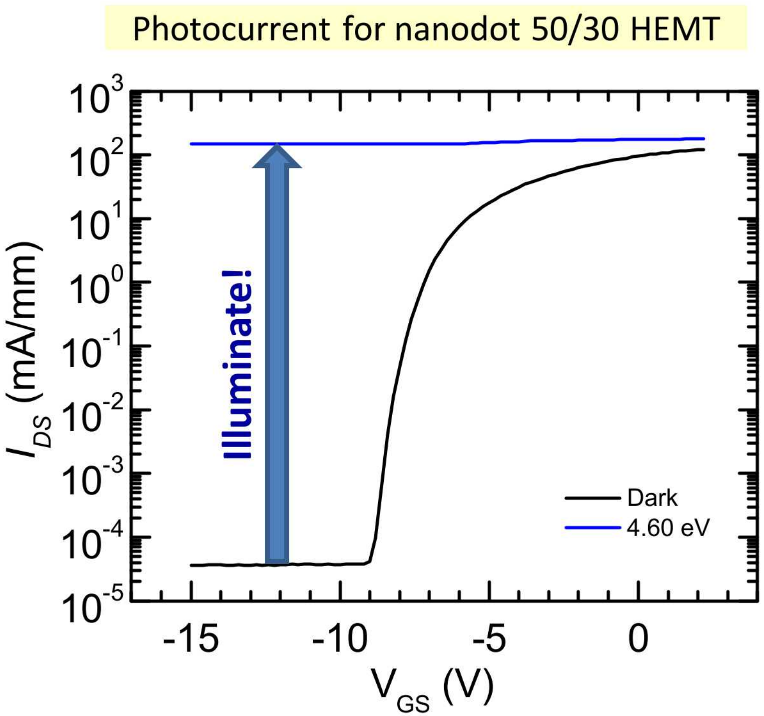


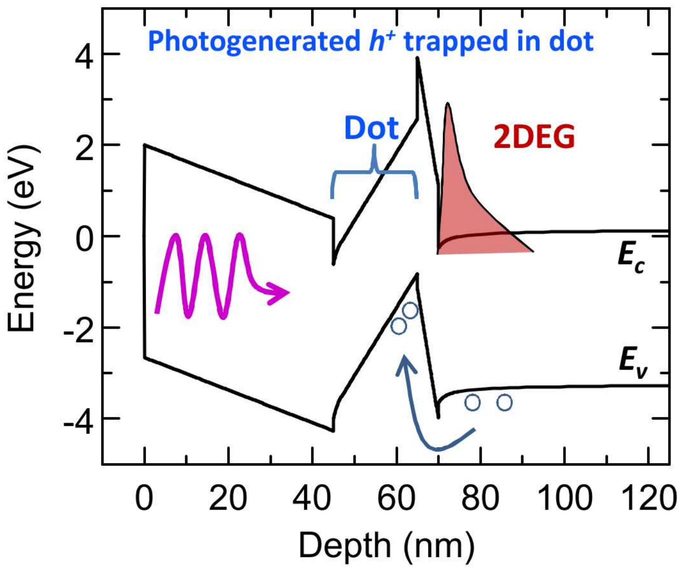
Transfer characteristics of nanodot 50/30 HEMT



- $Al_{0.3}Ga_{0.7}N$ HEMTs with GaN nanodots retain good ohmics and gate control
- Small hysteresis indicate GaN nanodots do not act like traps in dark

45/30 nano-dot HEMTs exhibit strong photosensitivity



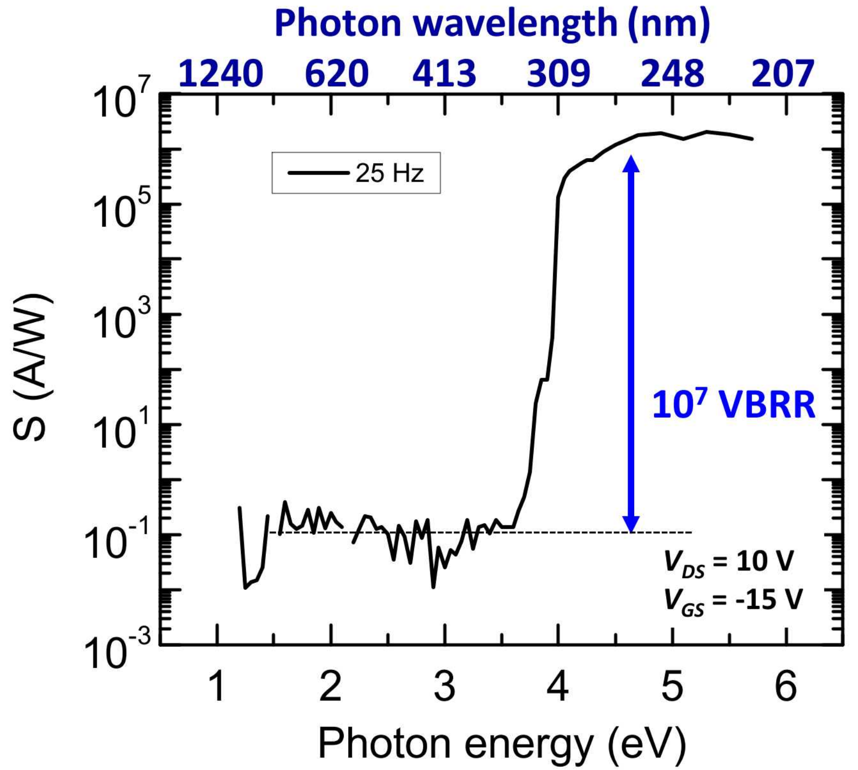


- Nanodot HEMTs exhibit large increase in I_{DS} under UV illumination
- Increase in I_{DS} indicates holes are being localized on nanodots

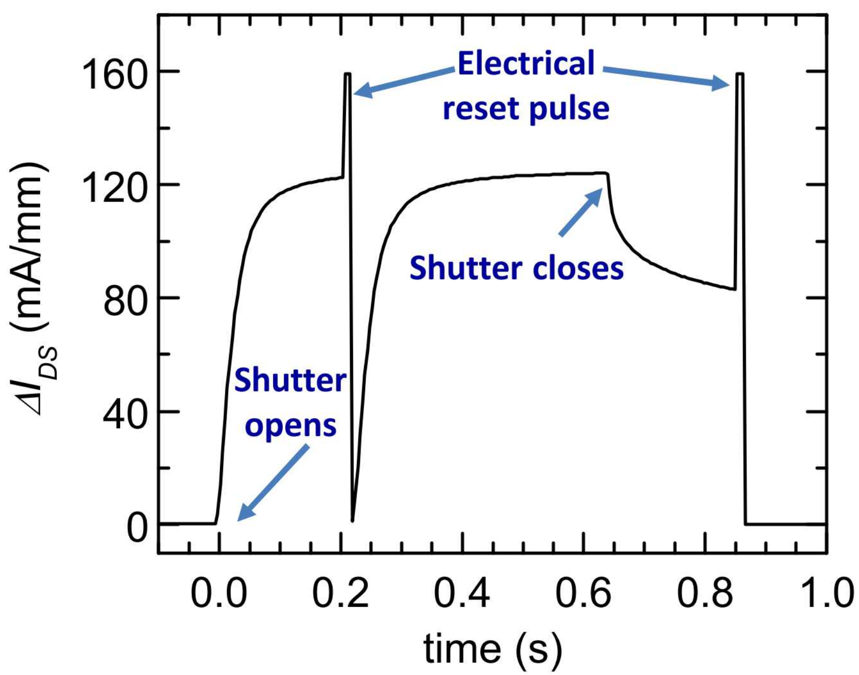
Visible-blind photoresponse for nanodot HEMTs

AA1

Responsivity of nanodot 50/30 HEMT



Photocurrent transient



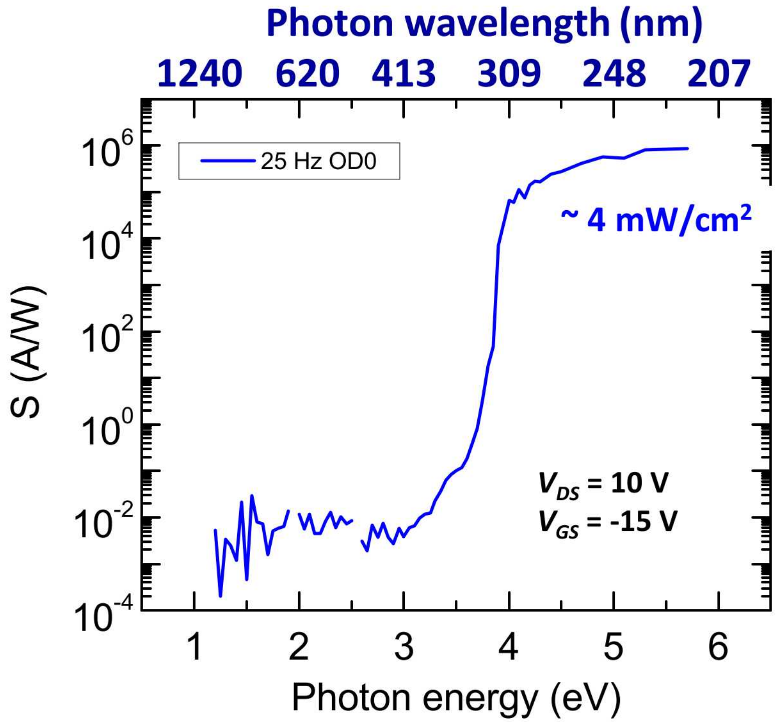
- Responsivity > 10^6 A/W and 10^7 visible-blind rejection ratio
- ~ 50 ms rise time and rapid I_{DS} reset using $+V_{GS}$ gate pulse

Slide 14

AA1 Armstrong, Andrew, 7/1/2019

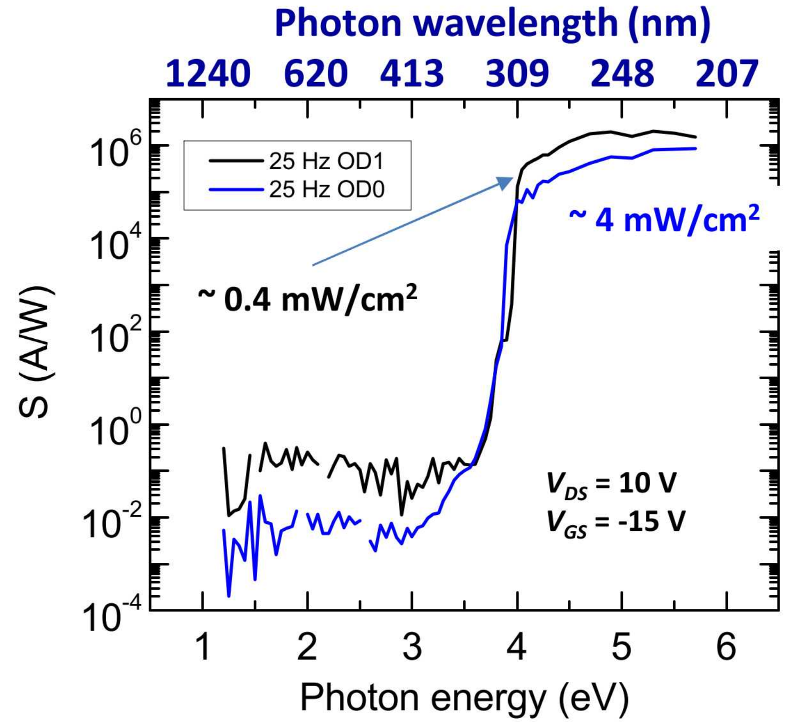
Hole recombination with channel limits dynamic range of operation

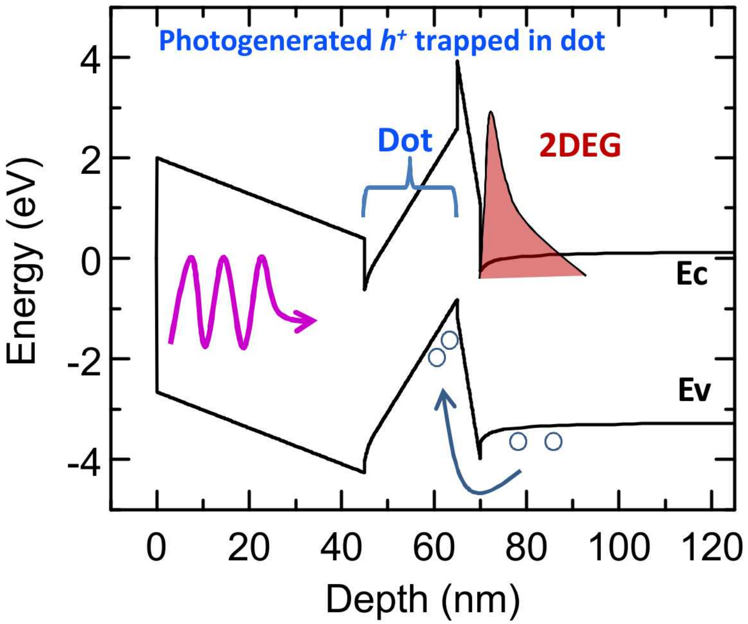
Responsivity of nanodot 50/30 HEMT



Hole recombination with channel limits dynamic range of operation

Responsivity of nanodot 50/30 HEMT

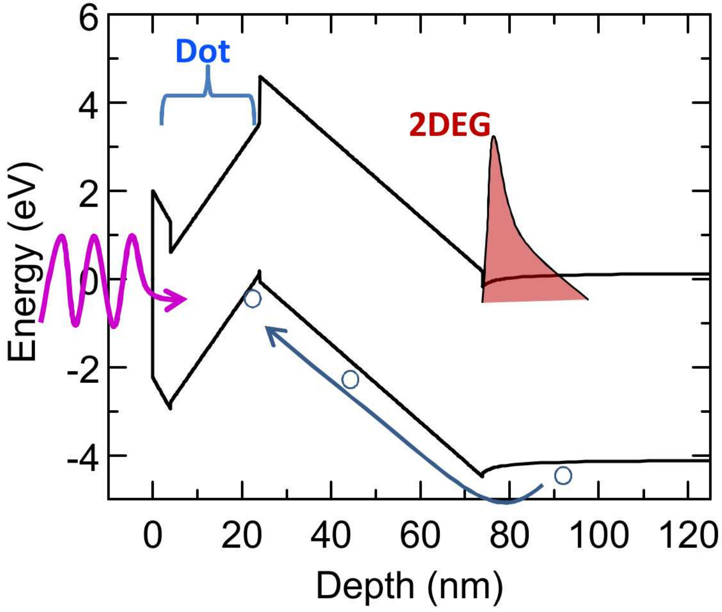




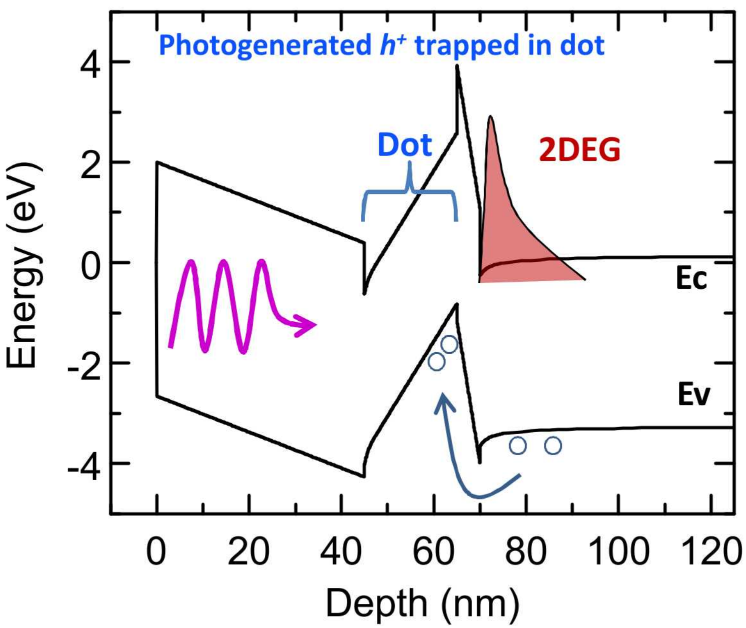
- ➢ *S* increases when intensity reduced 10x
- ➢ Sharp drop off of *S*, i.e. ΔI_{DS}, when intensity reduced > 10x
- ➢ Hole recombination with nearby channel requires large optical generation rate

Designed new heterostructure for improved dynamic range

Near-surface nanodots

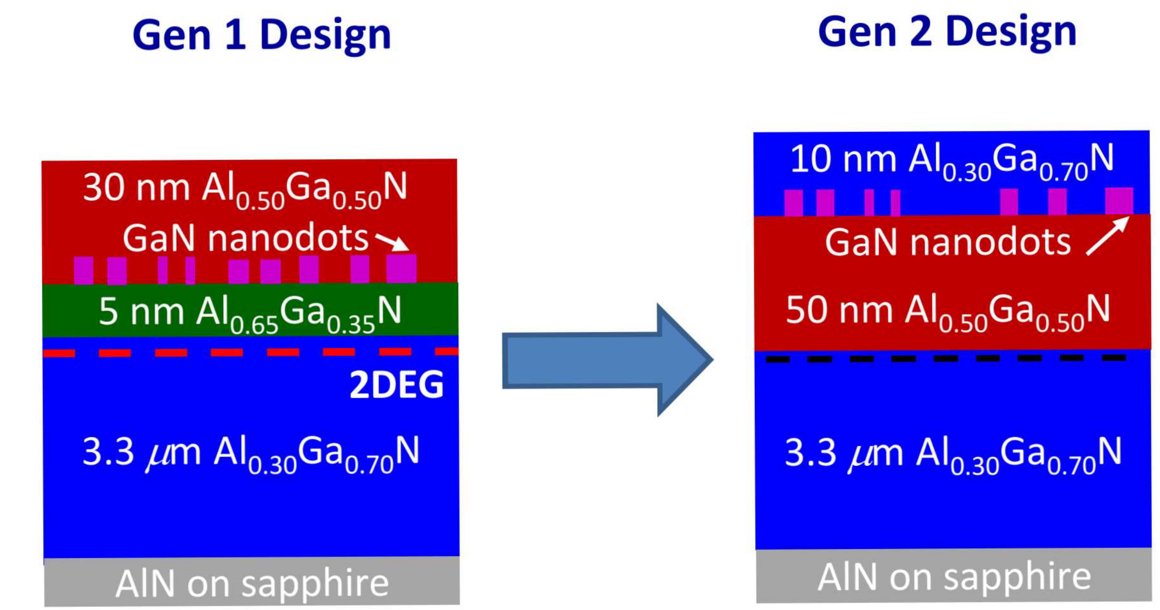


Near-channel nanodots



- New heterostructure places nanodots near surface to separate localized holes and electrons
- Enable much wider dynamic range and greatly increase *S*

Next Design



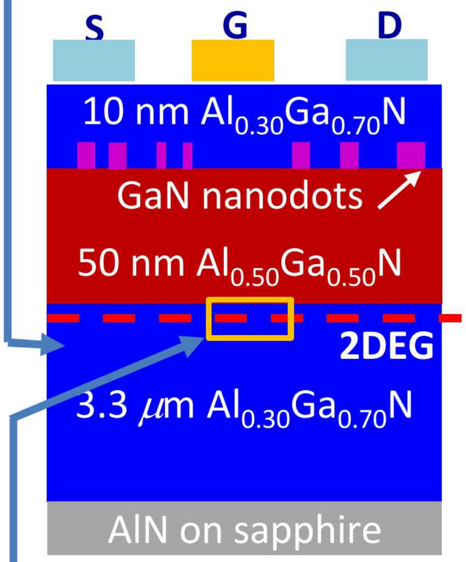
Nanodots under thick barrier | **Nanodots under thin cap**

Grow dots closer to the surface to improve hole lifetime within the nanodots

Gen 1 AlGaN Quantum Dot Floating Gate HEMT

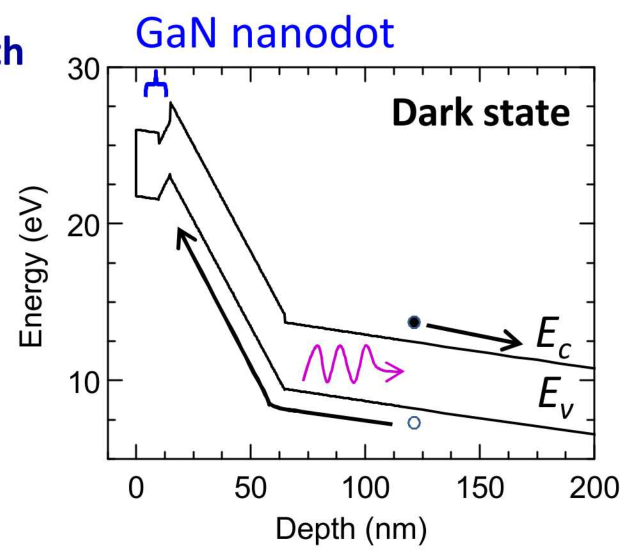
Vis-blind AlGaN QD-FG HEMT

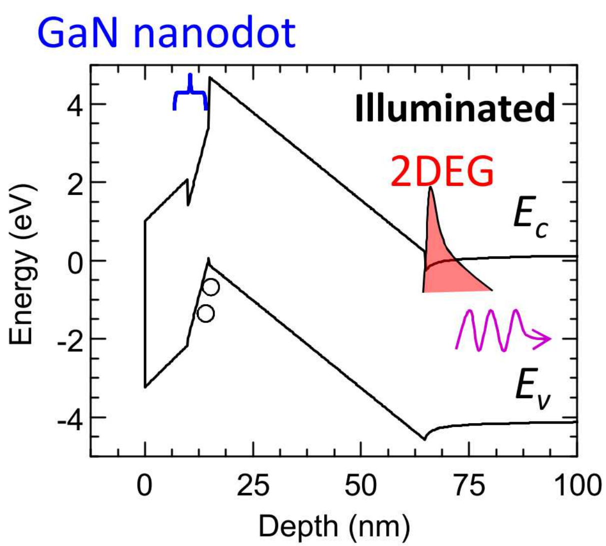
Channel Egap sets absorption wavelength



2DEG under gate modulated by charges occupying nanodots

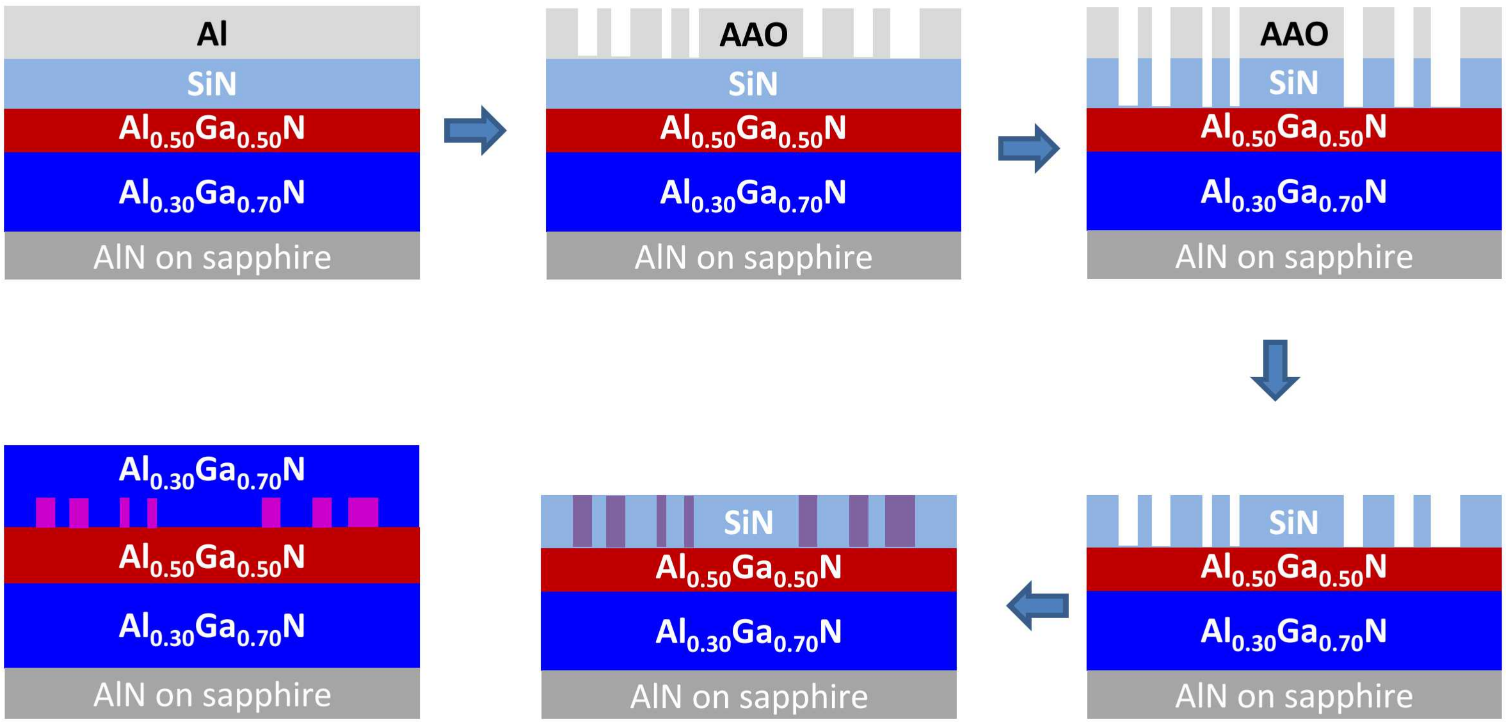
Energy Band Diagram





- AlGaN capping layer over GaN nanodots aids capture and keep holes from surface

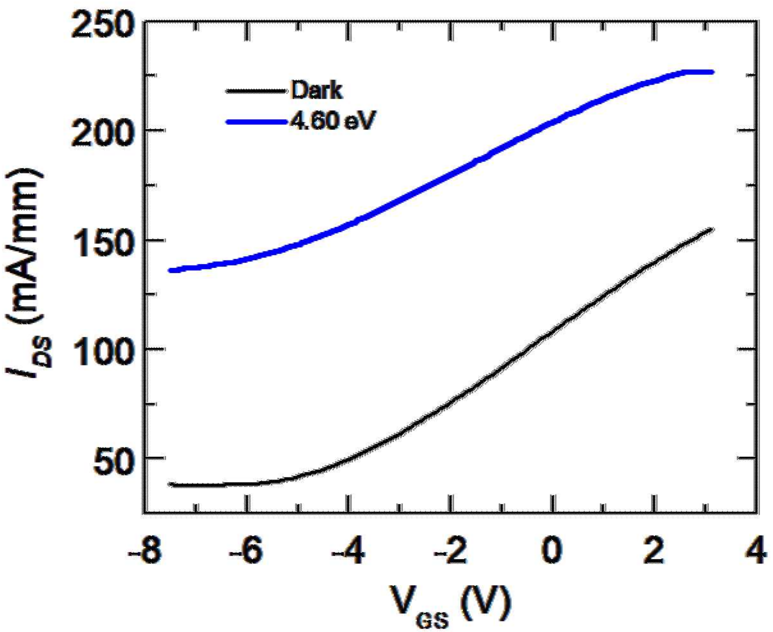
GaN nano-dot patterning and growth



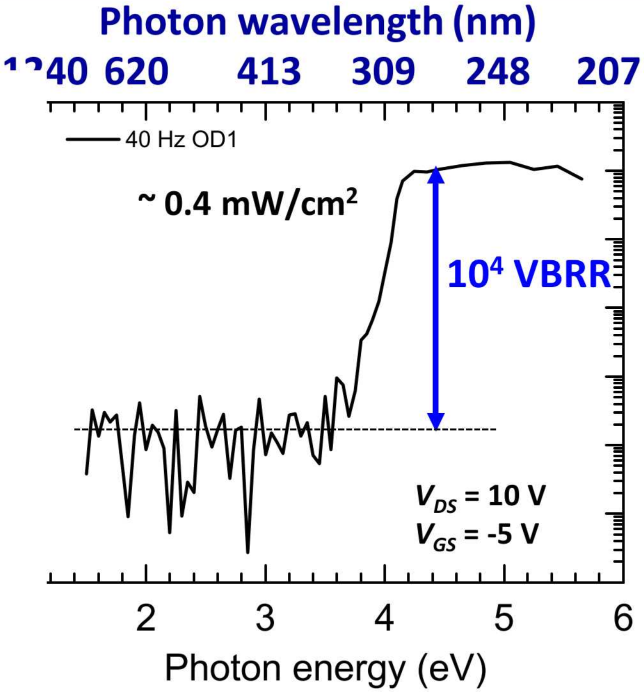
- Similar epitaxial and process flow to form embedded GaN nanodots

Near-surface nanodot HEMT exhibits strong photoresponse

Transfer characteristics of near-surface nanodot HEMT

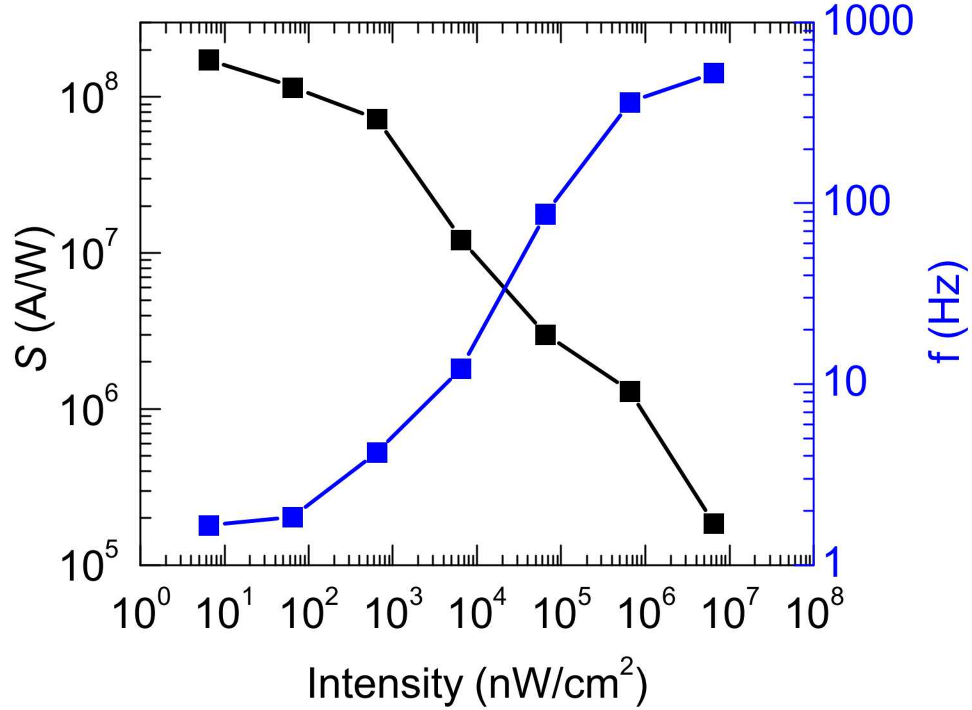


Responsivity of near-surface nanodot HEMT



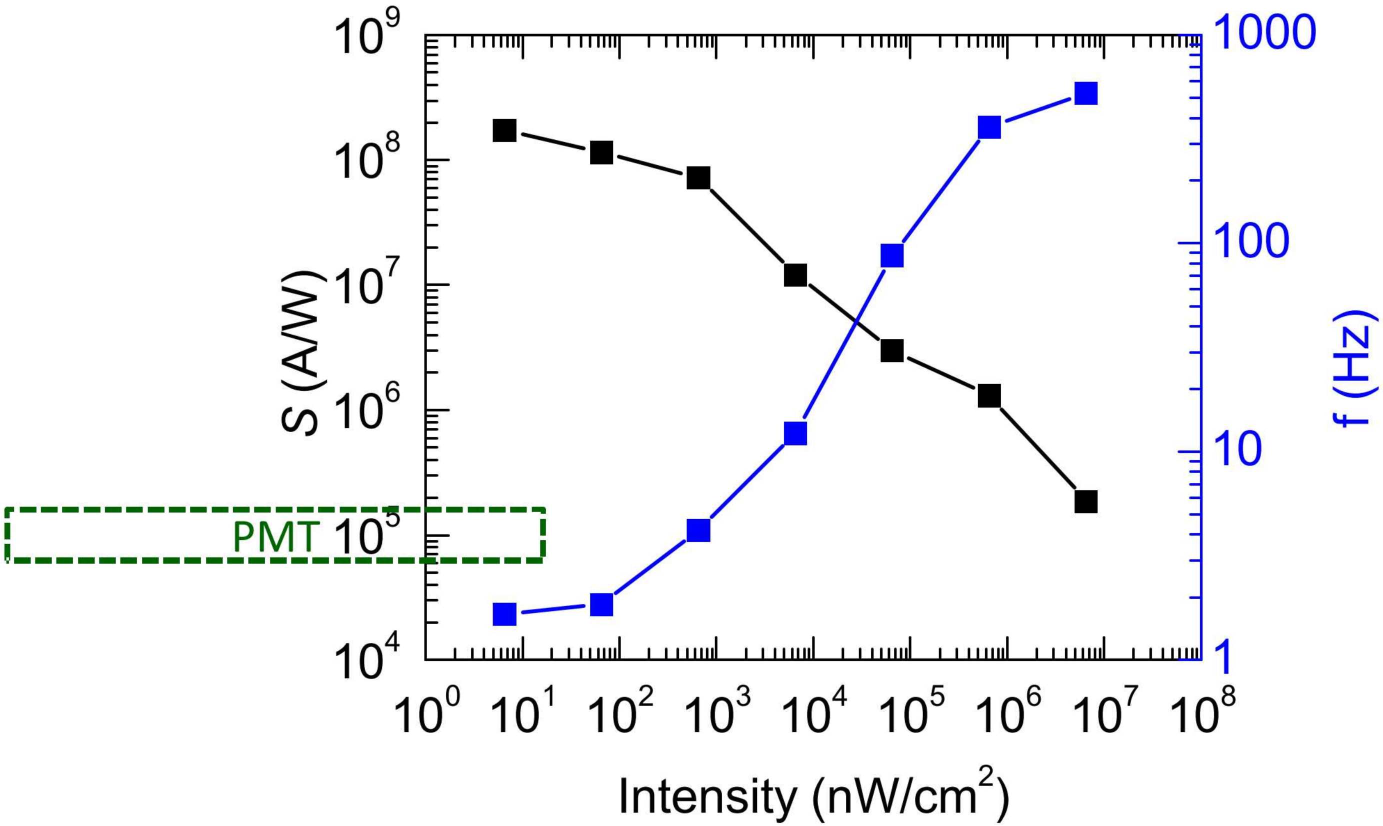
- Near-surface nanodot HEMT did not pinch off (atypical template effect)
- Degraded VBRR ~ 10^4 but still achieved large *S*

Near-surface nanodot HEMT capable of photon counting



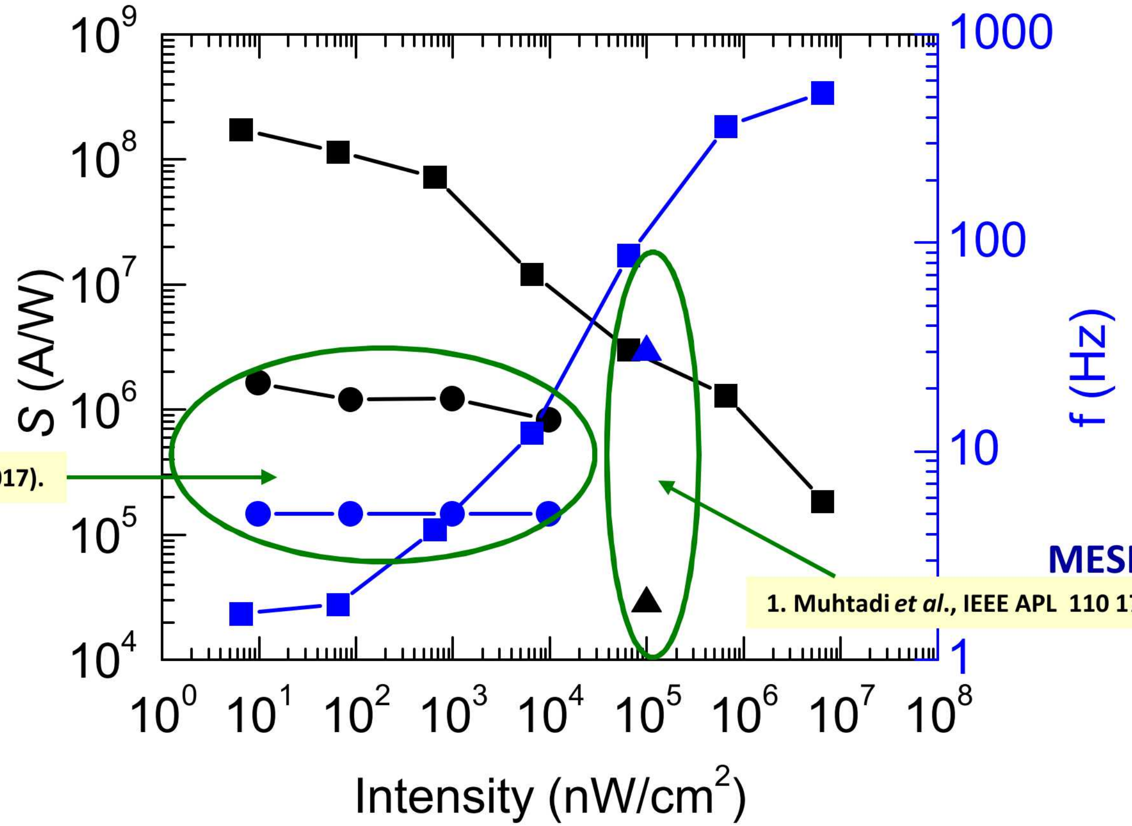
- Moving nanodots near surface enabled operation over large dynamic range of intensity
- Peak $S = 1.7 \times 10^8$ A/W = 100 pA/γ sufficient for UV photon counting
- Gain-bandwidth product > 1 GHz

Near-surface nanodot HEMT compares well to PMT



- ➢ PMTs achieve much lower dark current and 100 MHz but at 10^5 A/W
- ➢ Responsivity >> bandwidth for threat detection
- ➢ High *S* enables very high sensitivity and very low false alarm rate

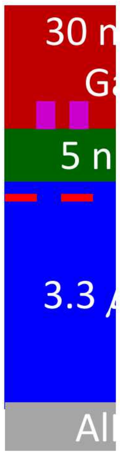
Nanodot HEMT compares well to AlGaN MESFET and MSM



- Nanodot HEMT exhibits larger *S* and *f* than AlGaN MESFETs[1] or AlGaN MSM[2] devices
- Important to note that MSM and MESFET devices were solar-blind
- Next step is to increase nanodot HEMT channel composition to achieve solar-blind detection

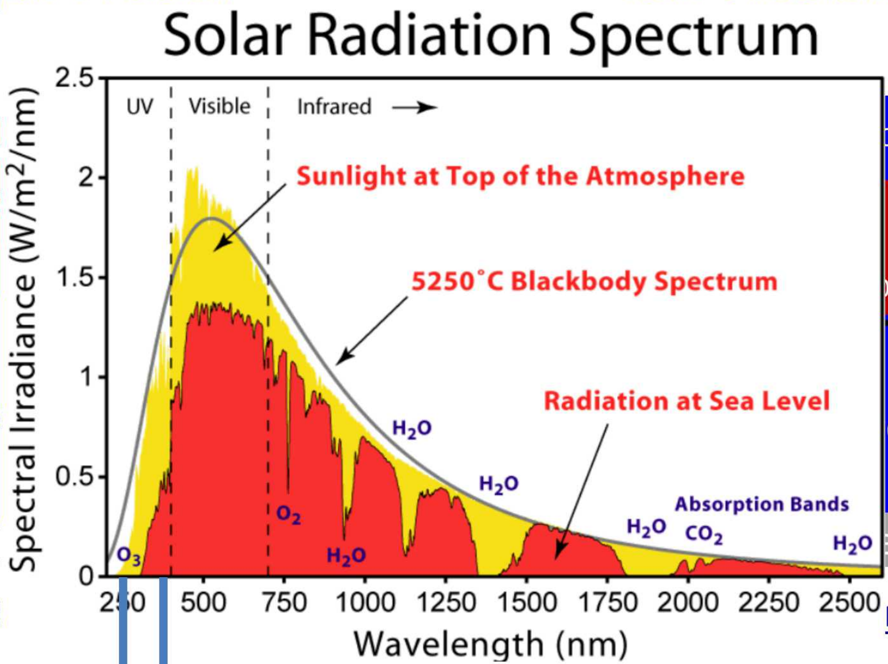
Next Design

Gen 1 Design



Nanodot

Gen 2 Design



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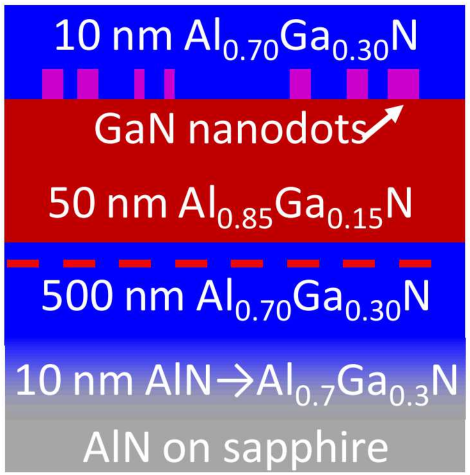
n cap

Gen 3 Design



Nanodots under thin cap
Increased Al composition

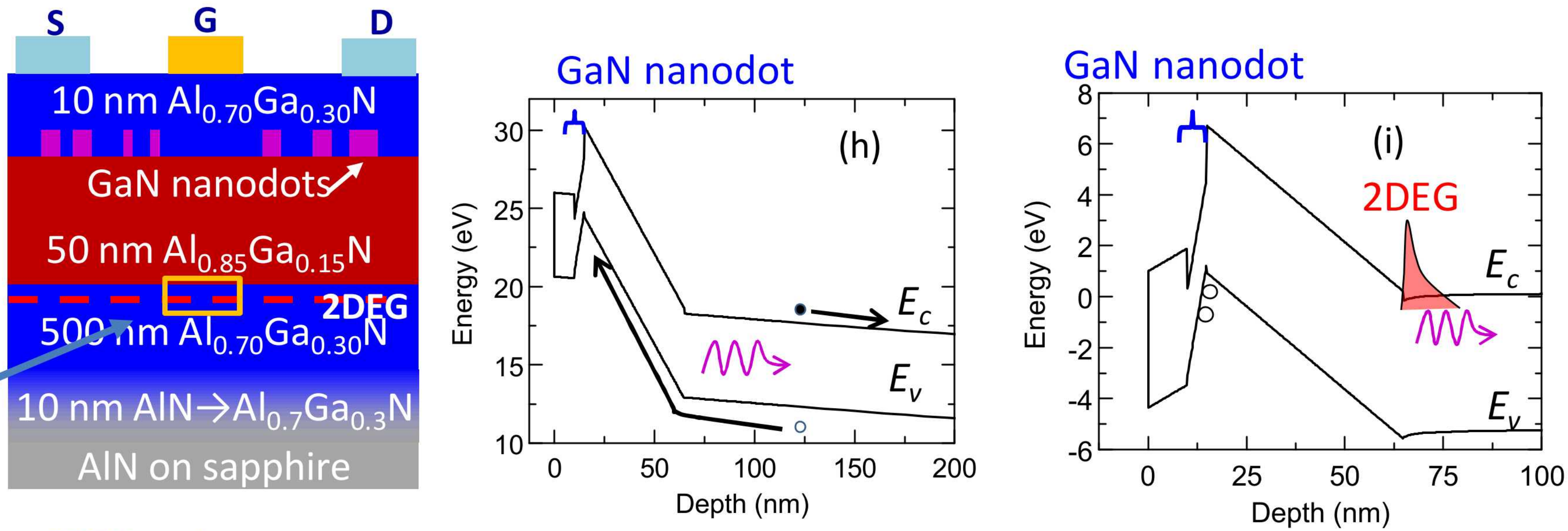
Gen 3: < 250 nm

Modify Al composition to go from vis-blind to solar-blind

Gen 1 and 2: < 375 nm

Increase Al content for solar-blind detection

Channel Egap sets absorption wavelength

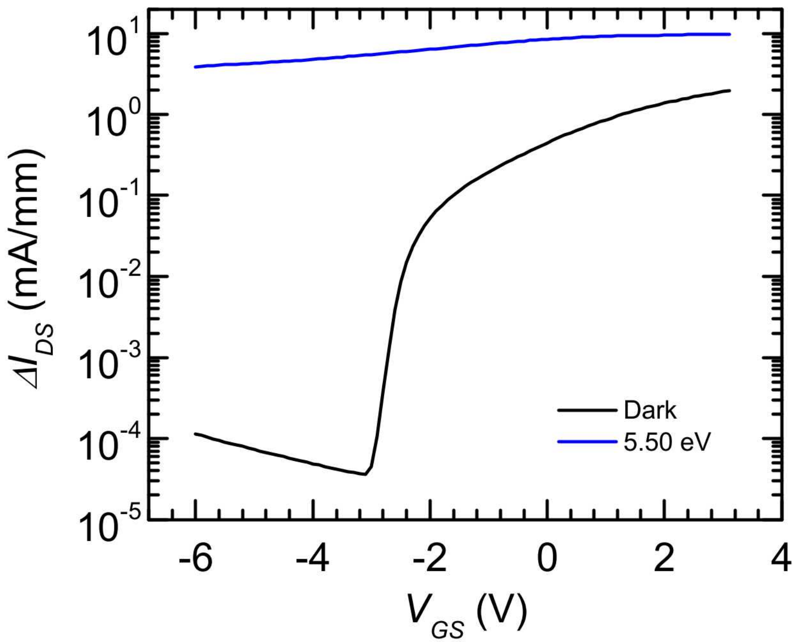


2DEG under gate modulated by charges occupying nanodots

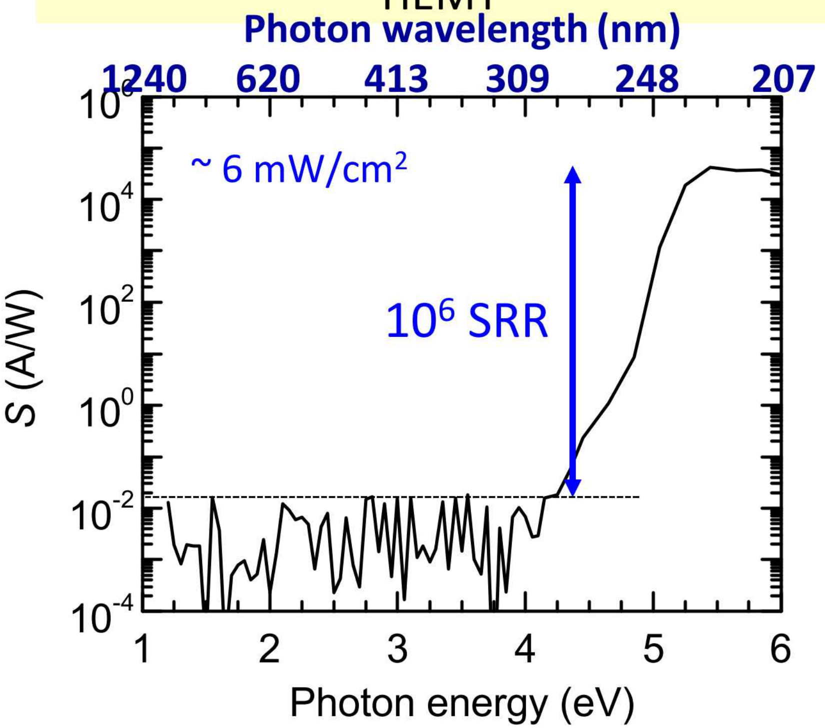
- Same design can be used for solar-blind detection by increasing HEMT Al content
- Same GaN nano-dot formation process

Increase Al content for solar-blind detection

Transfer characteristics of near-surface nanodot HEMT



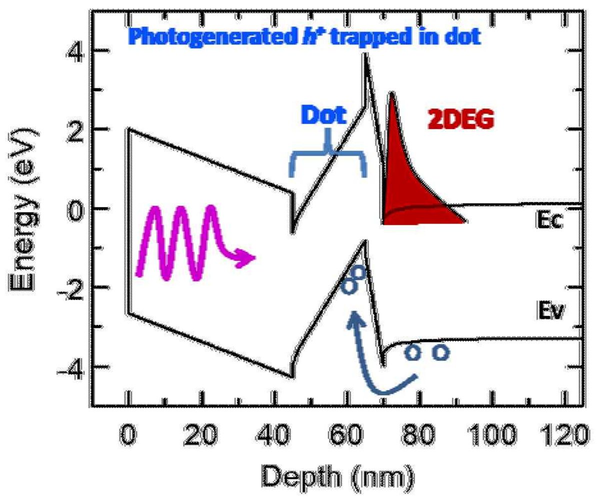
Responsivity of near-surface nanodot HEMT



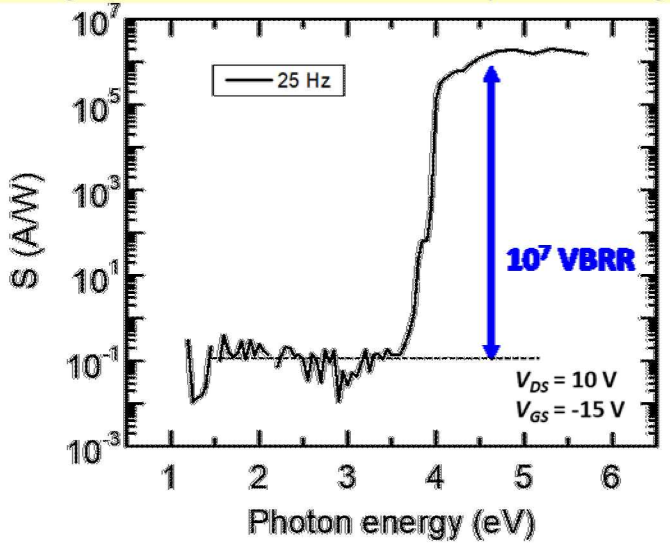
- Similar qualitative device photo-response
- High solar-rejection ratio
- However, poor ohmic contacts limit I_{DS}, ΔI_{DS} and thus S

Summary

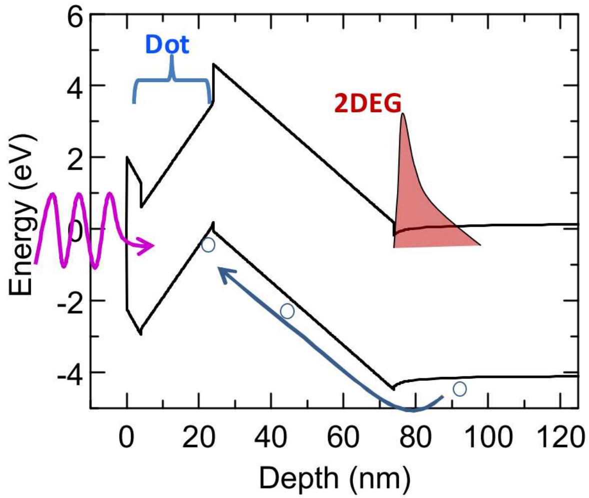
AlGaN HEMT with nanodots near channel



High S and VBRR but limited dynamic range



AlGaN HEMT with nanodots near surface



Vis-blind nanodot AlGaN HEMT with G•BW > 1 GHz