Advances in APDs for the UV at Northwestern University

presented by

Mel Ulmer*

Dept of Physics & Astronomy

with R. McClintock, V. Vesheni, E. Cicek and M. Razeghi
Center for Quantum Devices

Northwestern University

*m-ulmer2@northwestern.edu

Tel 847-491-5633

Why single photon detection (SPD) is good : Compare SPD (top) with EMCCD performance (bottom)

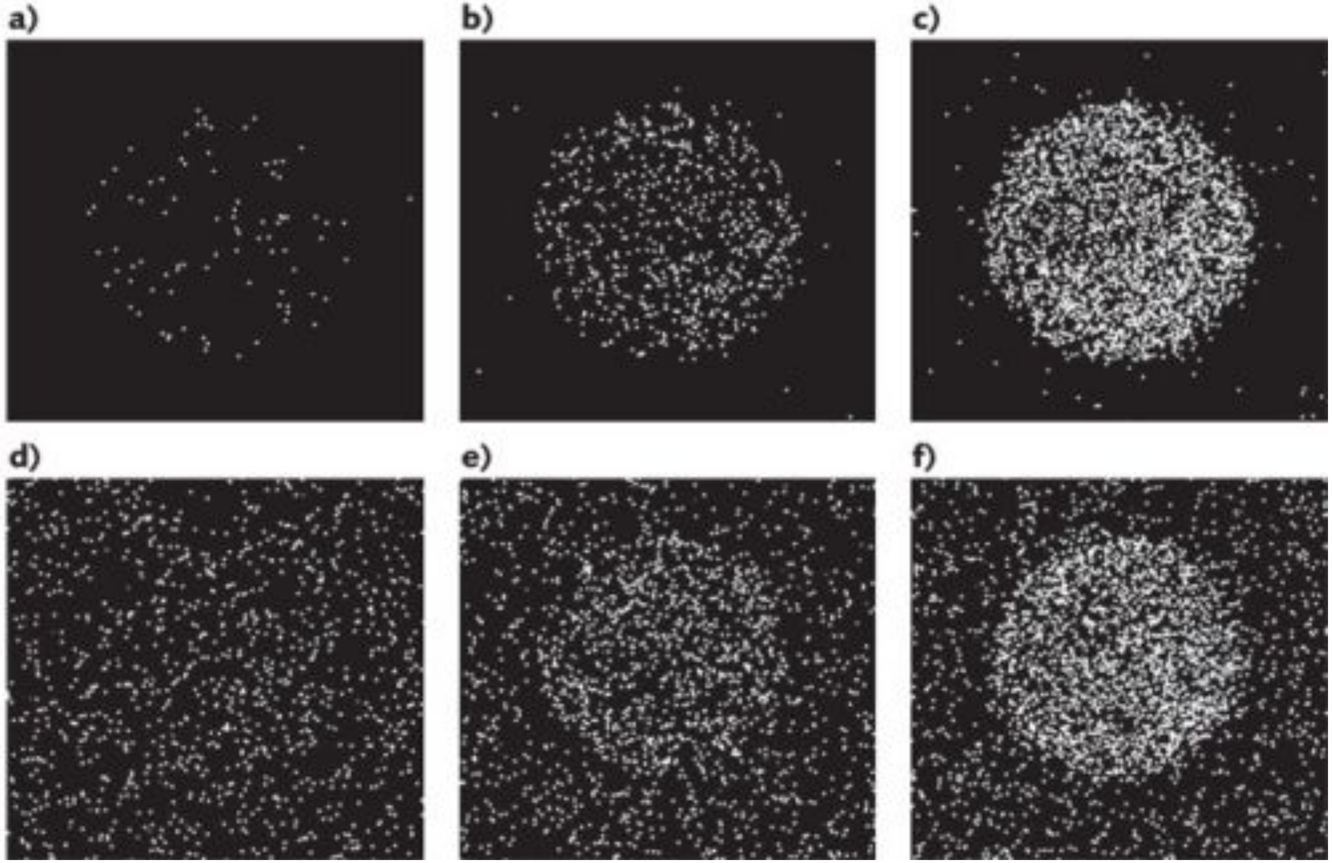


FIGURE 1. Images (400 × 400 pixels) taken of a constant-output 1.25-in.-diameter luminescent disk. 33, 250, and 1000 ms exposures were captured by a Stanford Photonics XR/Turbo-Z ICCD camera (a, b, and c, at -20°C) and a Hamamatsu ImagEM EMCCD (d, e, and f, at -70°C). The green emission was filtered at 550 nm to limit light to the nominal peak of the QE curves for each sensor. The ICCD camera detects 87 photons in the 33 ms exposure shown. The EMCCD cannot detect the object since clock-induced charge (CIC) noise exceeds the photon level within the target region of interest. (*Courtesy of Stanford Photonics*)

Now on to our work: on GaN APDs

Why is GaN good?

It is a wide [direct] band gap so:

It is intrinsically visible blind and hence allows for zero or minimal filtering to block by 10^6, the red leak

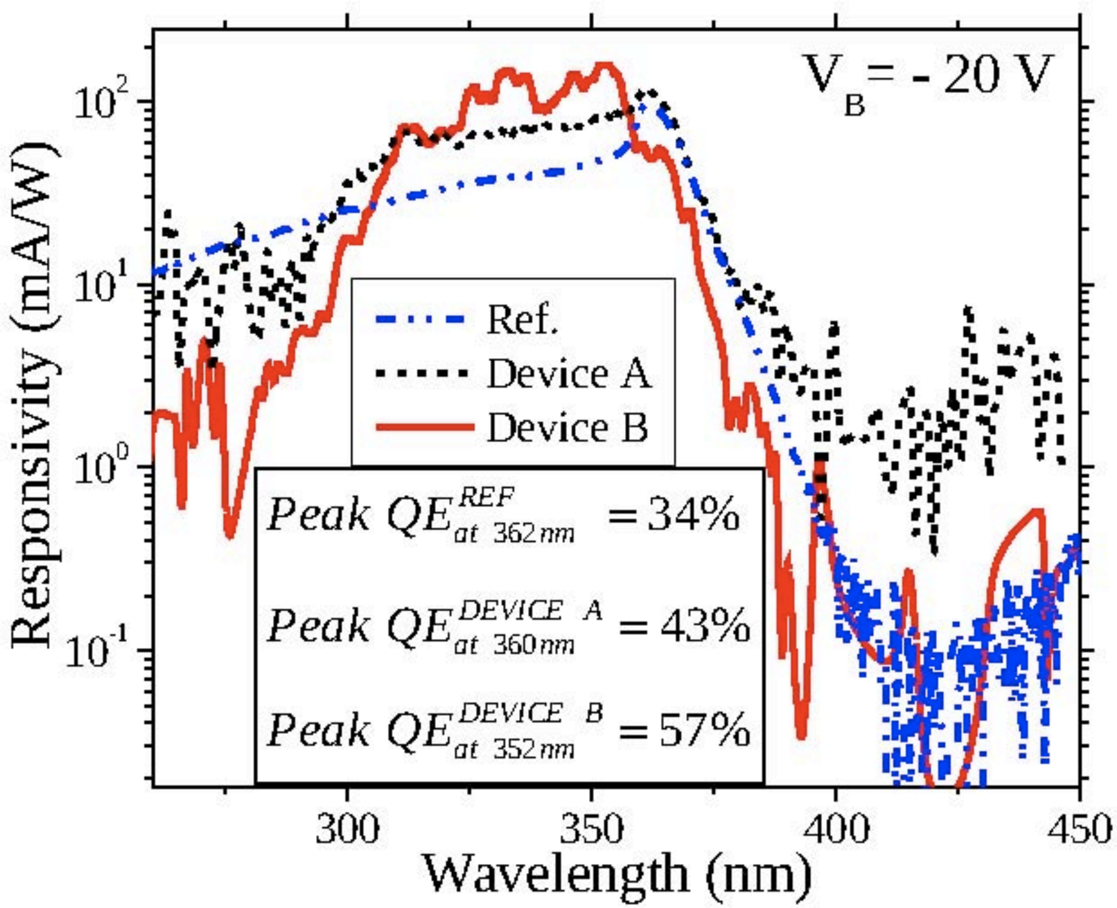
Solid state device can be operated at room temperature

Solid state device and is rad hard

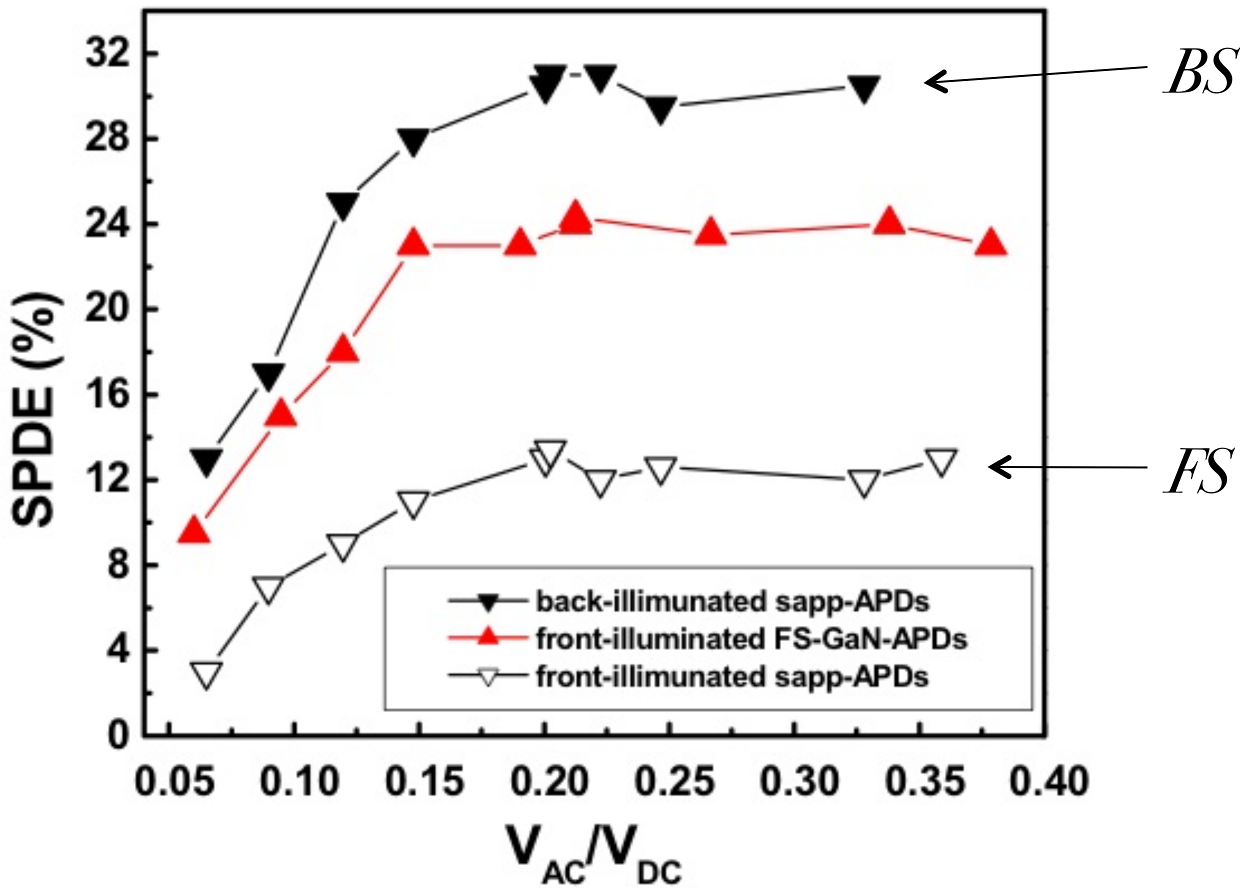
There are commercial applications of GaN => Non NASA funded work is being done to figure out how to make it better

Example of visible blindness

Rejection of red as good as almost 10^{-5}, measurement limited



Why Back side illumination is desirable

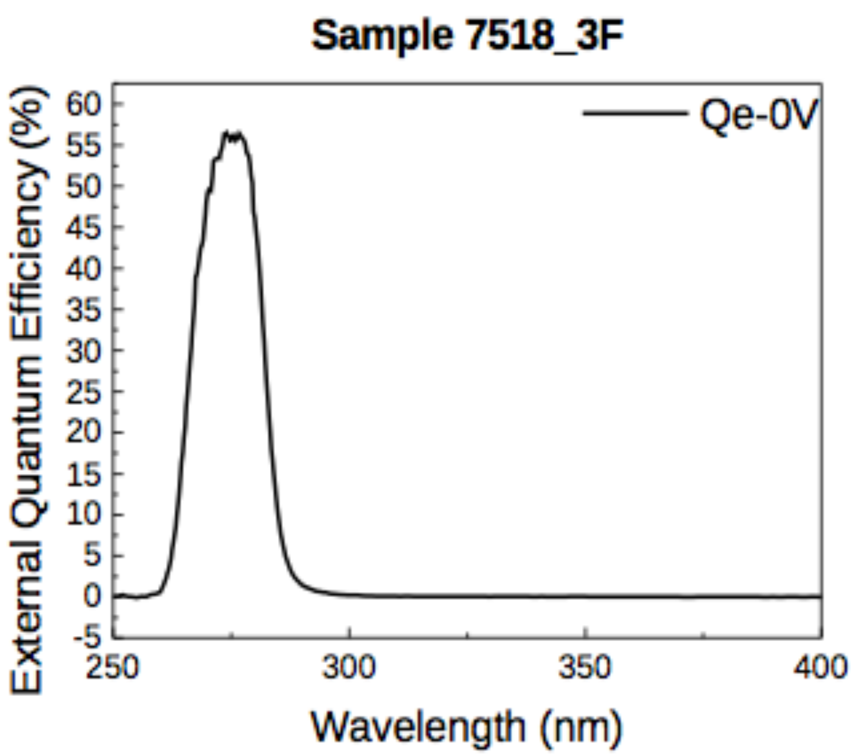


$V_{total} = V_{AC} + V_{DC}$
= constant

=> Eventually will remove non-active layers from back and do BS GaN grown => get over 50% QE (57% or more)

Another Proof Backside Illumination Does Improve QE

External Quantum Efficiency*



Peak EQE = 57%, more improvement to follow!

**The narrowness in wavelength of the EQE and responsivity is due to the setup: BS illumination. Eventually the offending layers will be removed.*

Where we are now:

With effectively zero dark count, 12% peak QE from front side =>
At least about 30% for BS illumination

Ways to improve are:

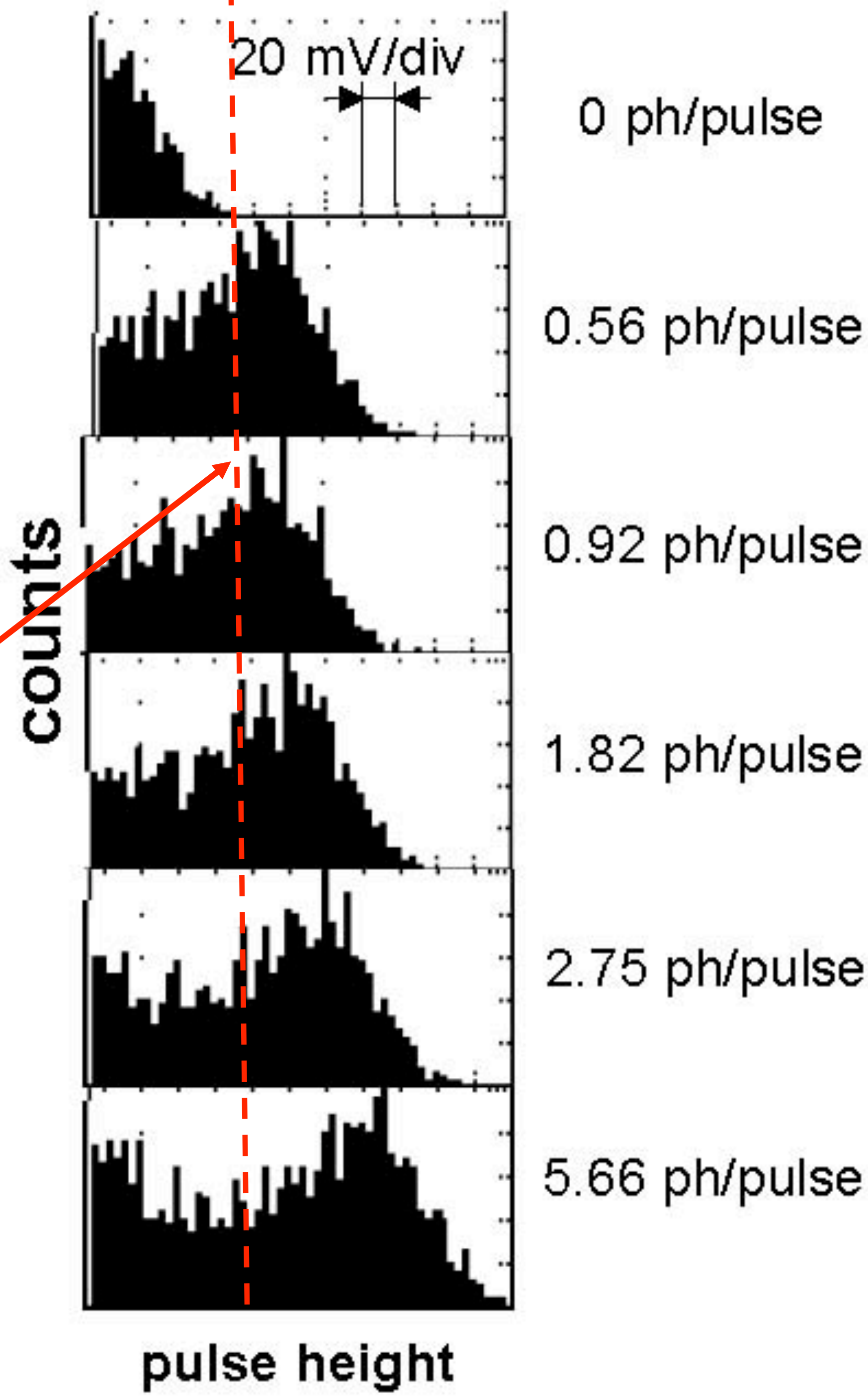
(a) Reduce defects to reduce dark count rate why and how much

(b) When all else fails, lower the operating temperature

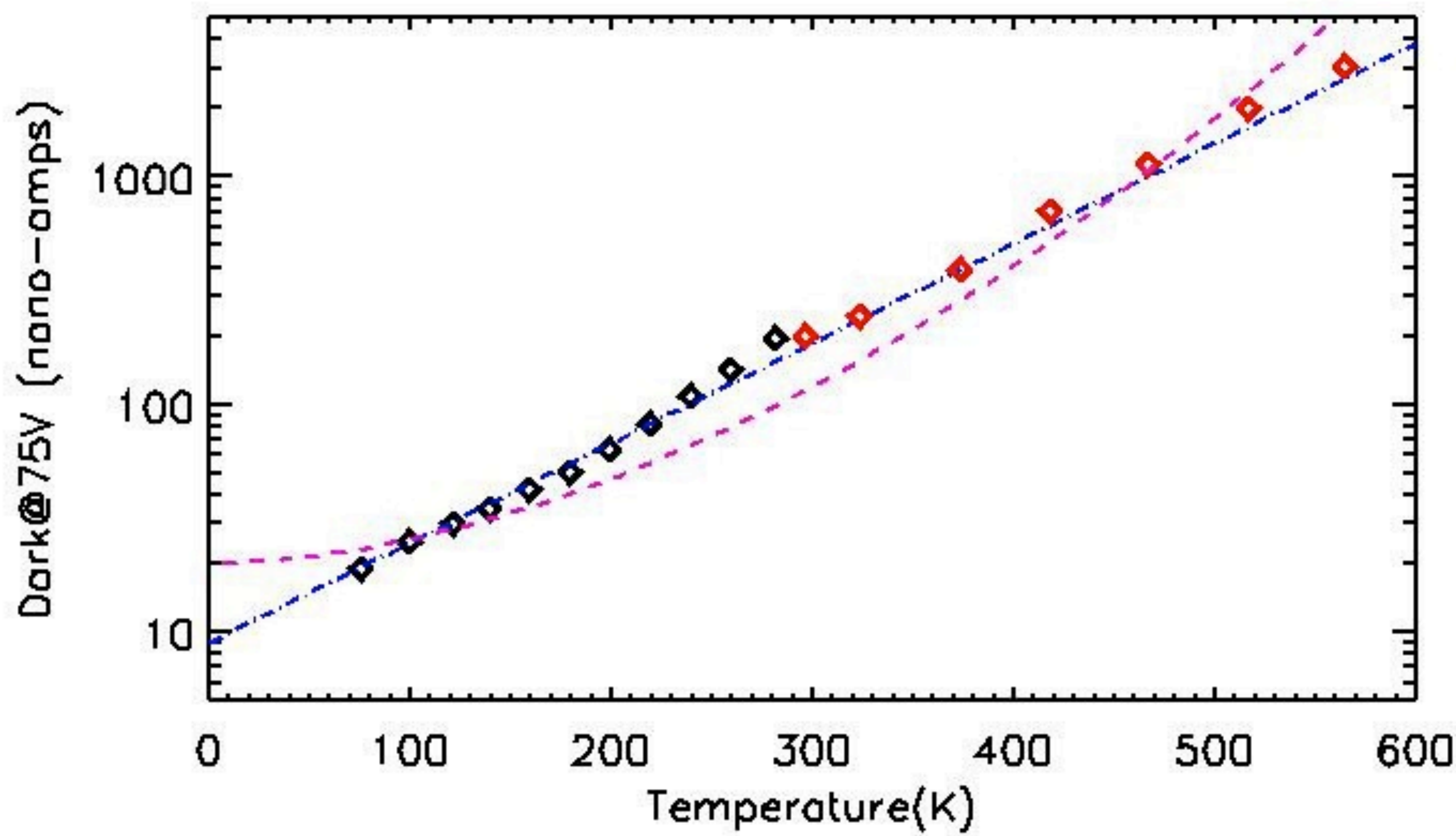
FYI, when we reduce the Dark Count rate to negligible amounts via pulse height discrimination (right now as we'll see , we lose about 50% of the photons this way

Pulse height distribution versus number of photons per pulse

If cut here still get about 50% detected (SPD) and nearly zero dark counts!



Straight line, good fit; magenta curve based on better E_a vs T fit (E_a vs T fit slide omitted for brevity) Bottom line is DC decreases, but only 20 x , and DC prop exp($-E_a/kT$) is defeated by E_a decreasing with T



The big leap forward will be with materials.
⇒ How much is necessary ?

Bottom line is about 1,000 should do if E_a varies even as slowly as the 0.2 power of threading dislocations.

Note for our case here there are only about 10^5 dislocations <=> there is a non-linear relationship between number of threading dislocations/unit area and Dark Current and Dark Counts =>

Details of the numbers:

Since $E_a(0)$ = the current value at room temperature is about 0.2 eV, 0.8 eV will do the trick of lowering the dark current (and associated dark counts) by 10^{10}

Using $\propto exp(-E_a/Tk_b)$

More TEM pics of threading dislocations

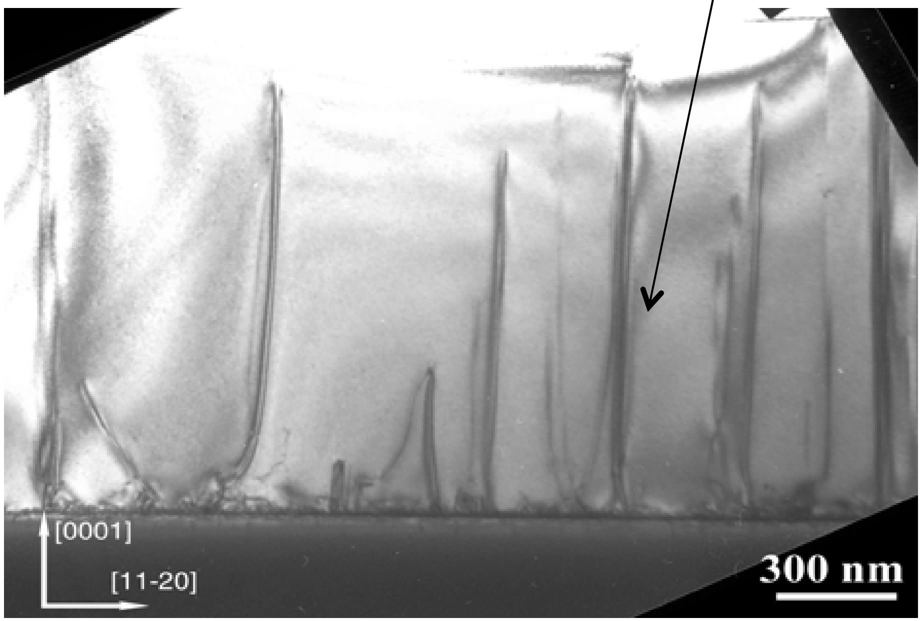


Fig. 1. Sample grown by MOCVD.

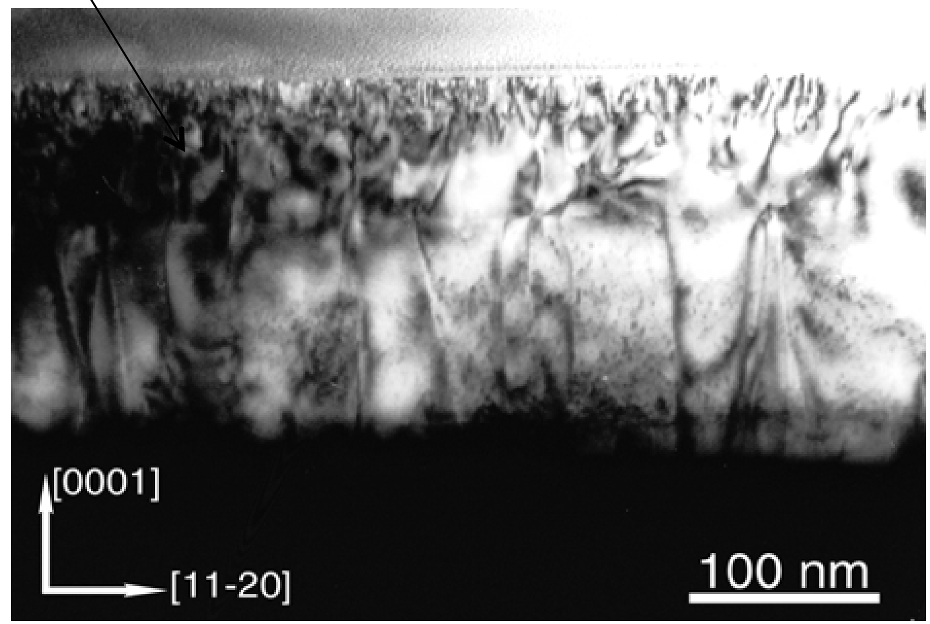
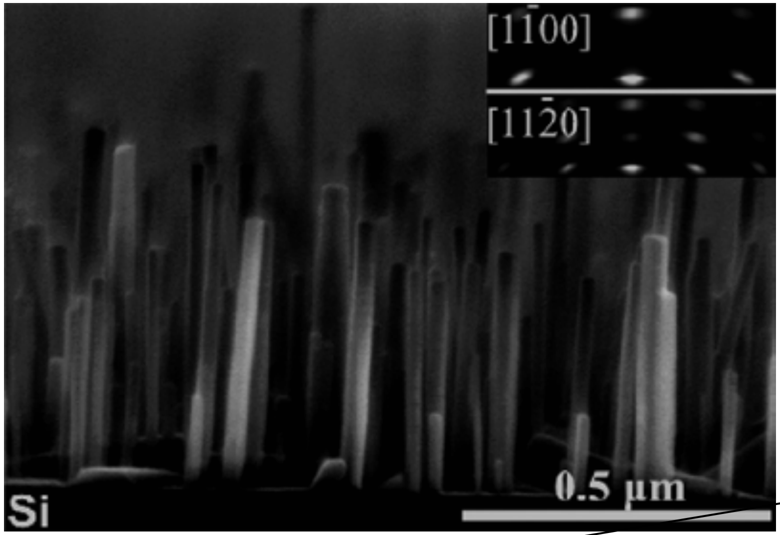
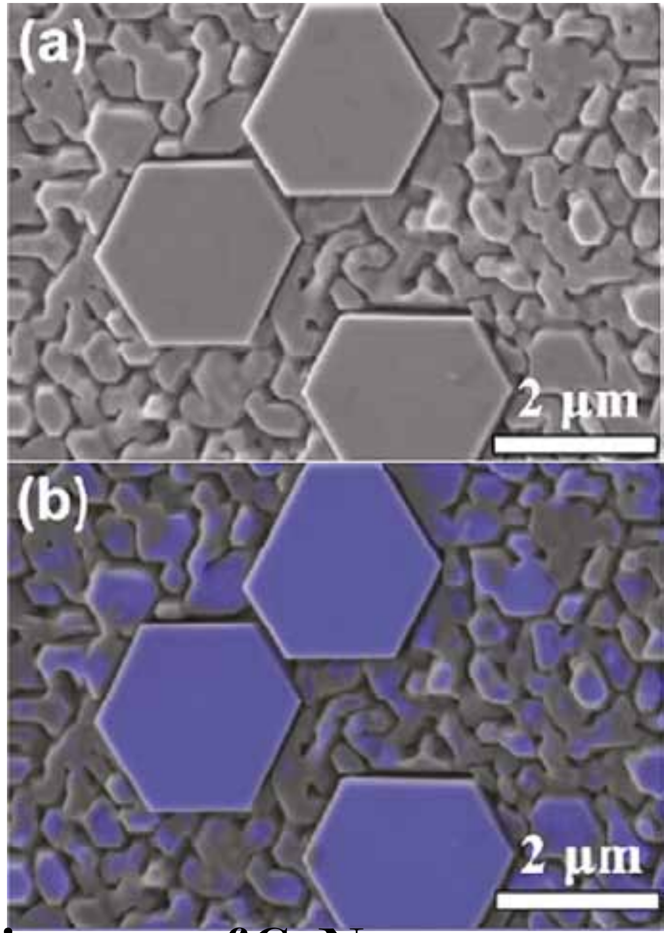


Fig. 2. Sample grown by MBE.

Note how much better MOCVD is versus MBE

We can reduce the threading dislocation number by lateral epitaxial overgrowth (LEO) on top of GaN nano- pillars.





"*Figure 5.* **(a) Top-view SEM and (b) top-view CL images of GaN microcrystals embedded in a network of smaller-sized grains. The emission from the GaN microcrystals is entirely homogeneous and noticeably stronger compared to that of the surrounding network of grains. No threading dislocations are observed." CL = Cathode Luminescent [imaging]**

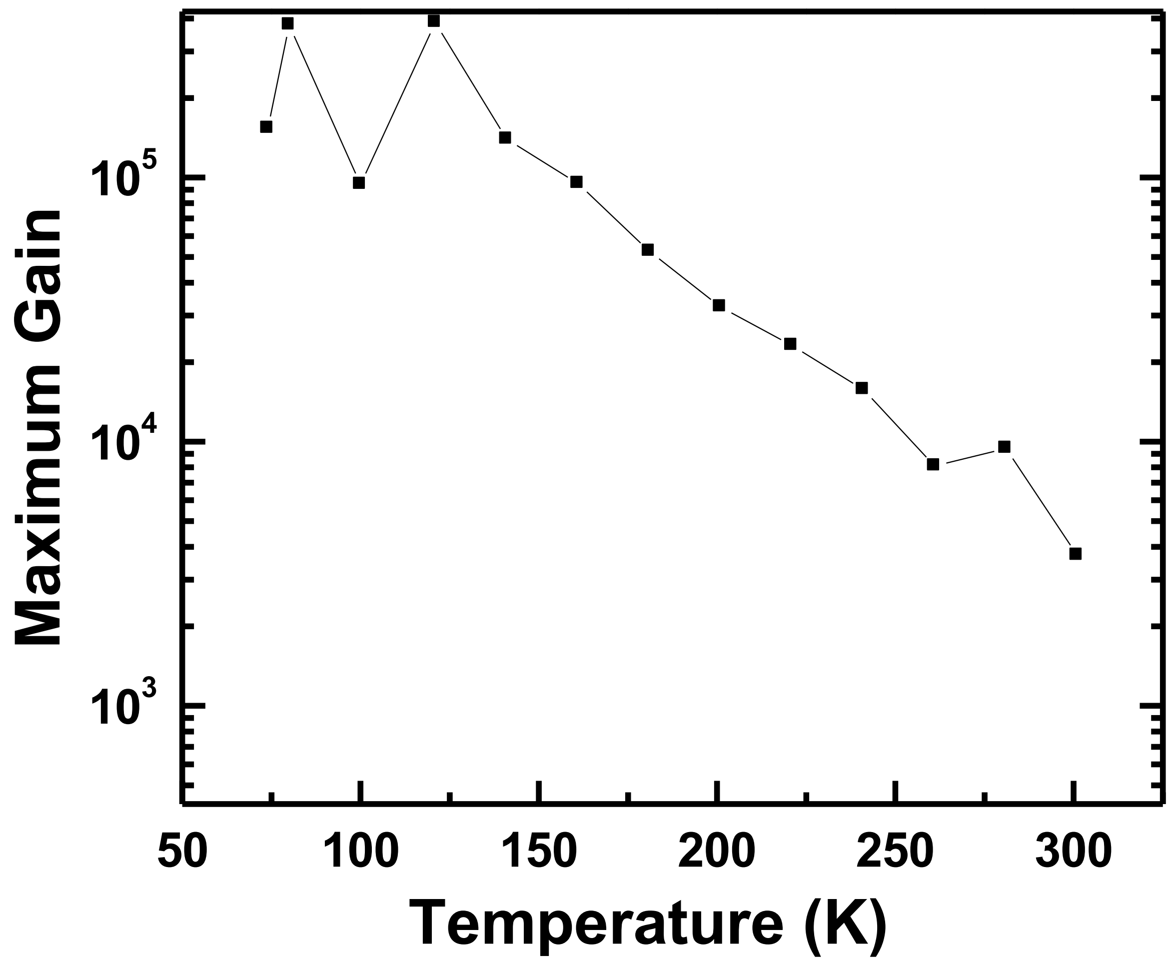
How about saying where we are now and lowering the temp instead?

TBD, however, is if there thermally produced pulses are significantly reduced in pulse heights while the photon-induced ones are not as we lower the temperature

This is real possibility that this will happen, as we achieved gain factors of more than 10^5 at low (near 100K) T

Temperature Dependant Performance of Visible-Blind Avalanche Photodiode(s)

Temperature Evolution of Maximum Gain



Summary and conclusion:

(a) The reduction in defects in GaN so as to reduce the dark counts/cm^2 that are competitive with MCPs may require a reduction in defects of only 1,000 over current values, but it is possible we can reduce these to zero. This is in reach with LEO techniques!

(b) Our best results to date would give us with zero dark counts, either 12% broad band or about 30% narrow band and out of band rejection of 10^{-4}-10^{-5} at least

(c) Lowering Temperature should decrease the dark counts and allow an increase in photon detection efficiency, but by how much is TBD

(d) With defect reduction and backside substrate removal, we expect be able to make cameras that have peak QE of > 60% broad band, and > 30% QE from 350 nm all the way to the Lyman limit with true photon counting and negligible dark count rates that are rad hard

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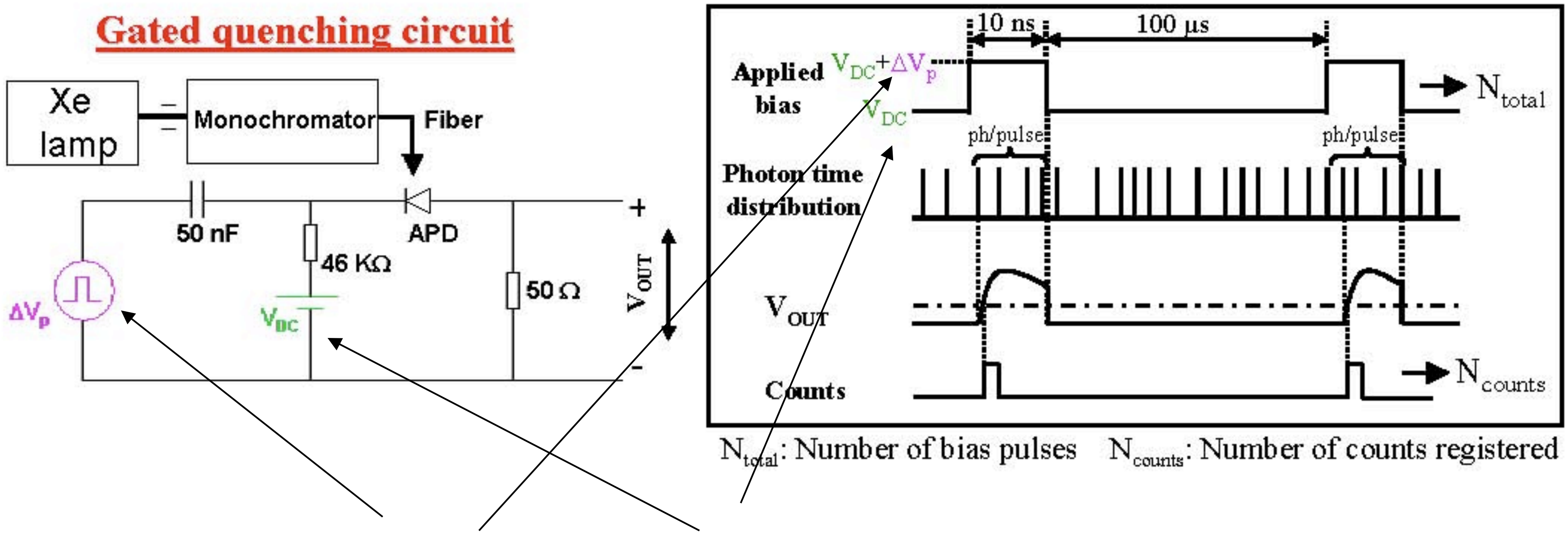
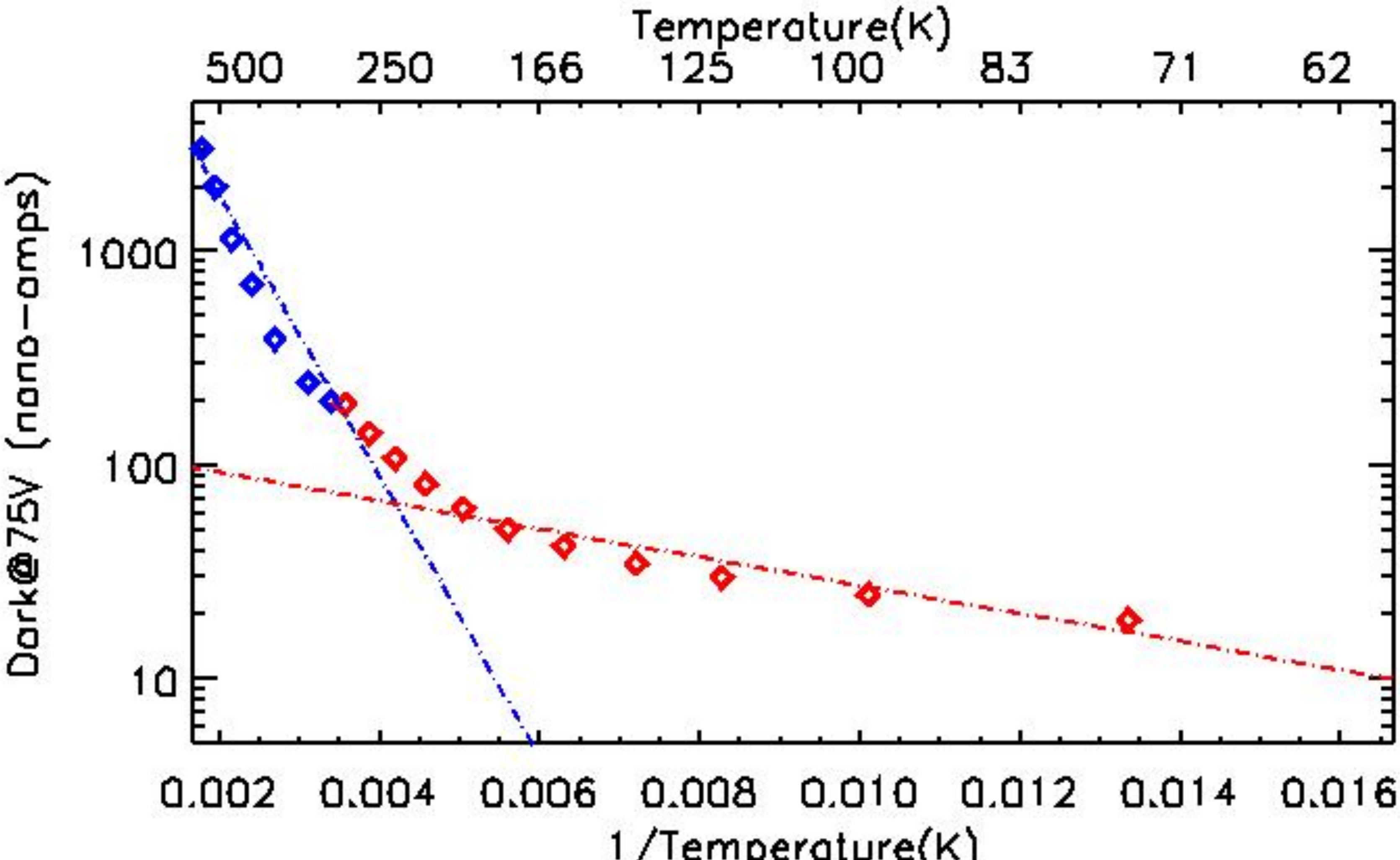
The End

Concept of gated circuit for testing the detection single pulses and also to quench trapped-on-defects electrons



AC voltage; DC Voltage

Expected is one straight line based on simple energetics:
Dark Current $\propto$ *exp*$(-E_a/Tk_b)$, *where* E_a = *dark current activation energy at avalanche onset. However,* E_a *varies with T, question is why??*



Fits of E_a vs T