SAND2013-3313C

Epitaxially passivated mesa-isolated InGaAs photodetectors

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Fabrication approaches for InGaAs detectors

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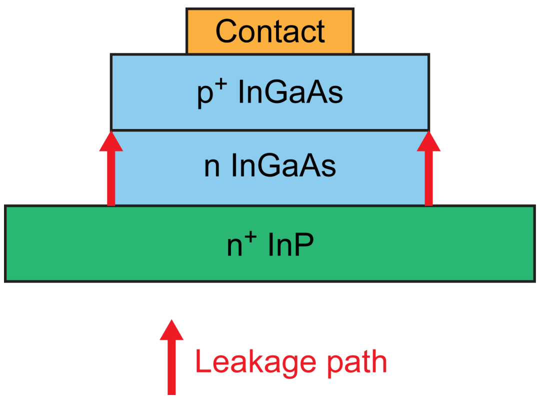
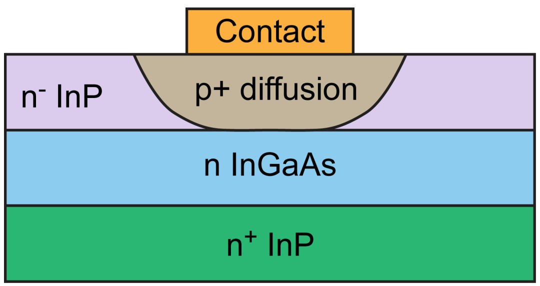
Conventional mesa



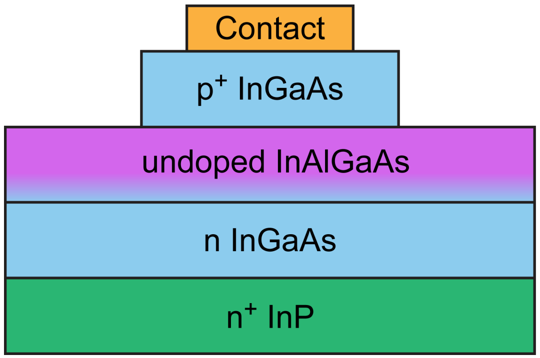
High surface leakage

Diffused contact



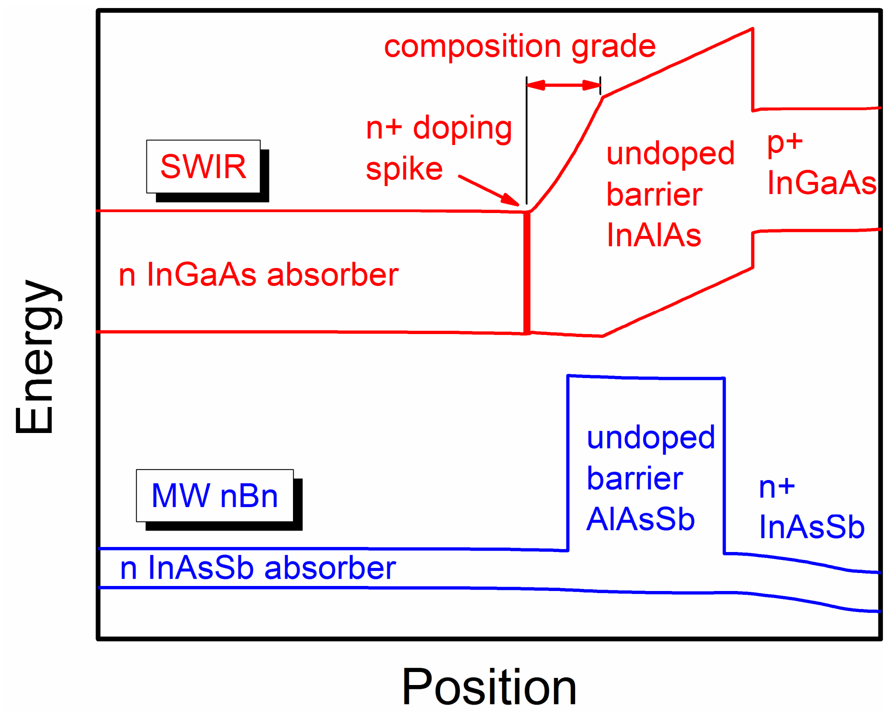
Very low dark current

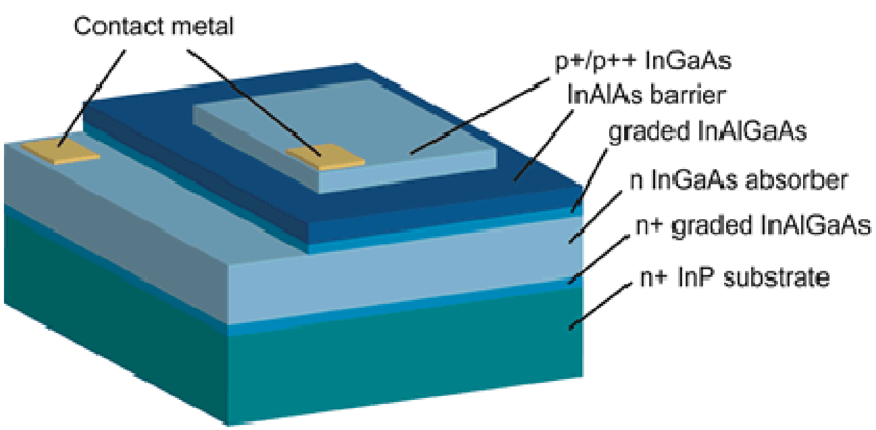
Epitaxially passivated mesa-isolated (this work)



Simple process
Potentially low capacitance

Comparison to the “nBn” detector





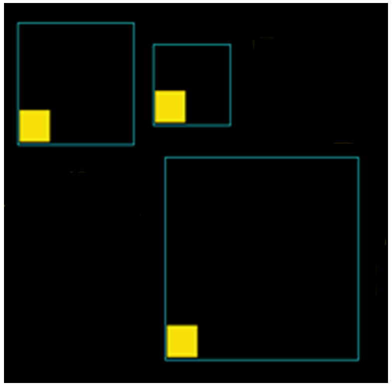
nBn greatly reduces
- Surface leakage
- Depletion region generation (G-R)

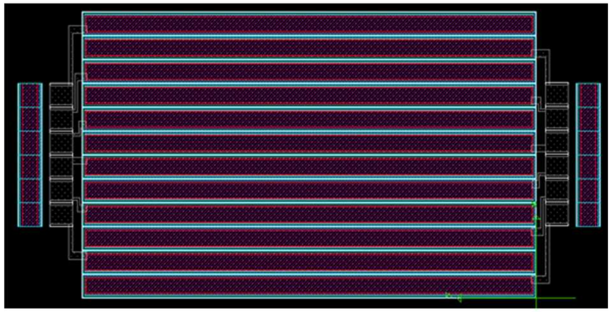
Principles of operation
- Optical e-h generation in absorber
- Collection of holes across barrier
- Barrier blocking of electron transport
- Surface passivation by barrier material

Similarity to nBn
- Large bandgap barrier passivation
- Minimal depletion region

Differences from nBn
- p-type contact mesa
  - Reduces e^- thermionic emission
- Graded absorber/barrier interface
  - Smooths VB discontinuity
- Interface doping
  - Prevents absorber depletion

Procedures





Epitaxial growth

Molecular beam epitaxy

Device fabrication

Square devices (200×200 - 500×500 μm^2)

Selective wet etch to InAlAs for mesas
Wet etch to absorber for absorber contacts
PdNiAu contact metal litho / evaporation / liftoff
Unguarded

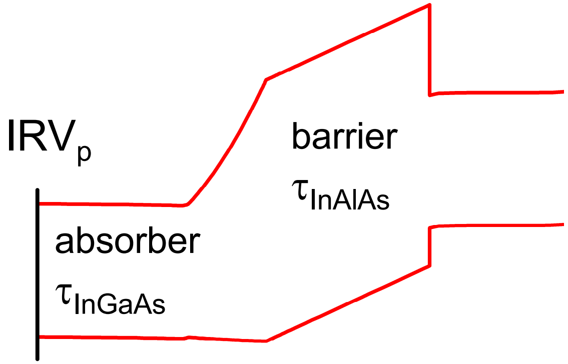
Linear devices (12.5-50×1000 μm^2)

Additional SiO_2 PECVD / RIE for pads
Proximity-guarded

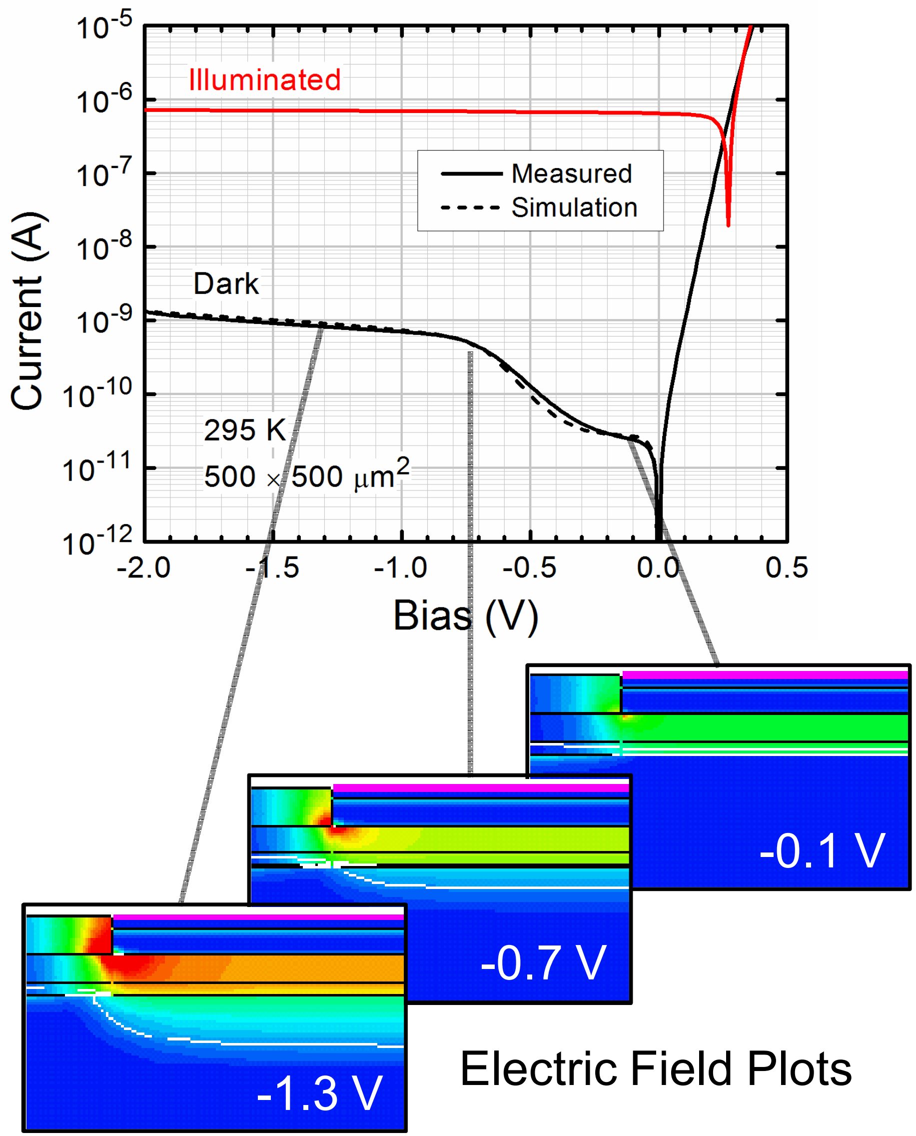
Simulation (1-D / 2-D)

Commercial drift-diffusion simulator (Sentaurus)

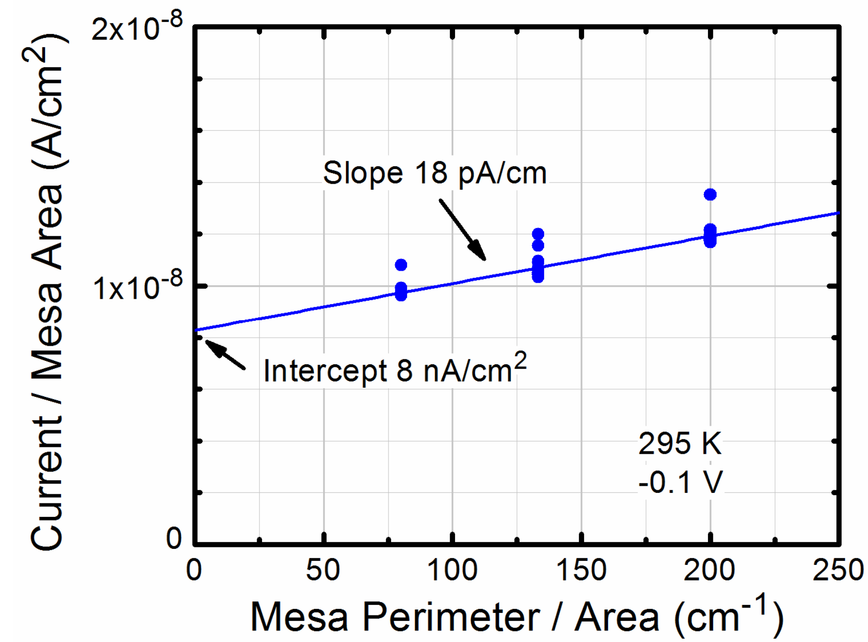
Initially assume InGaAs SRH lifetimes $\tau_e = \tau_h = \tau_{InGaAs}$
Include absorber / substrate interface recomb. velocity
Single $\tau_e = \tau_h = \tau_{InAlAs}$ in all InAl(Ga)As regions
Thermionic emission at barrier / p+ interface



I-V characteristics: Square devices



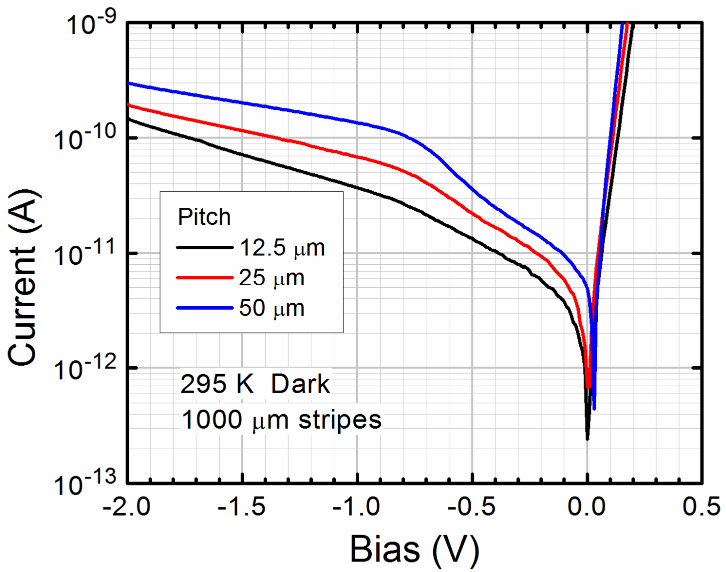
Electric Field Plots

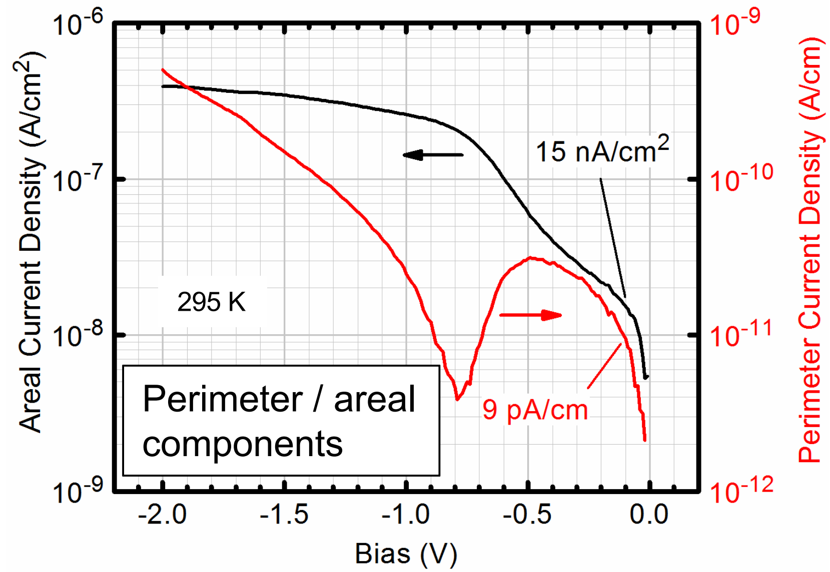


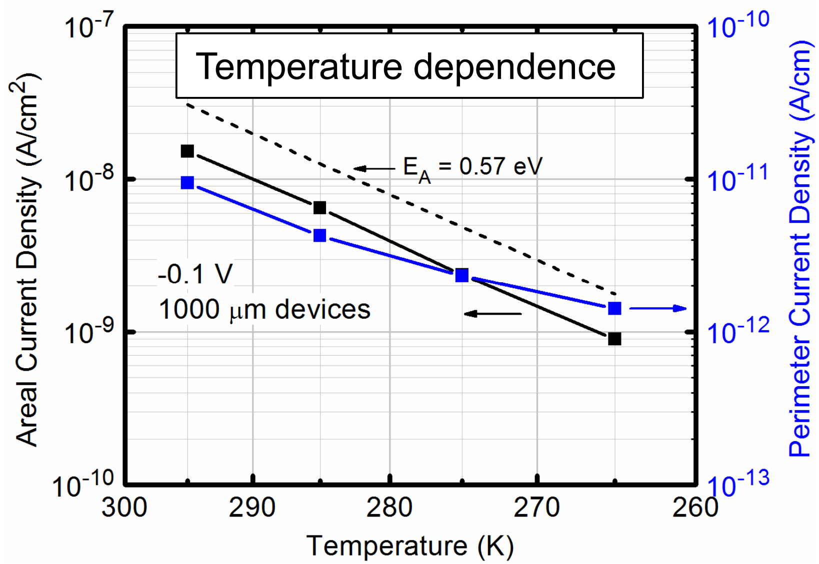
Parameters obtained from fit

- IRV_p 2000 cm/s
- τ_{InAlAs} 95 ns
- τ_{InGaAs} 7 μs
- spike doping 6×10^{17} cm^{-3}

I-V characteristics: Linear devices





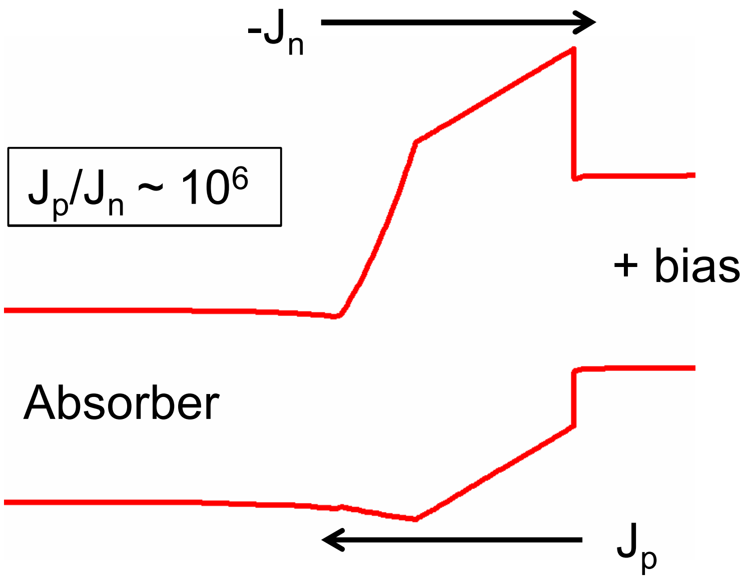


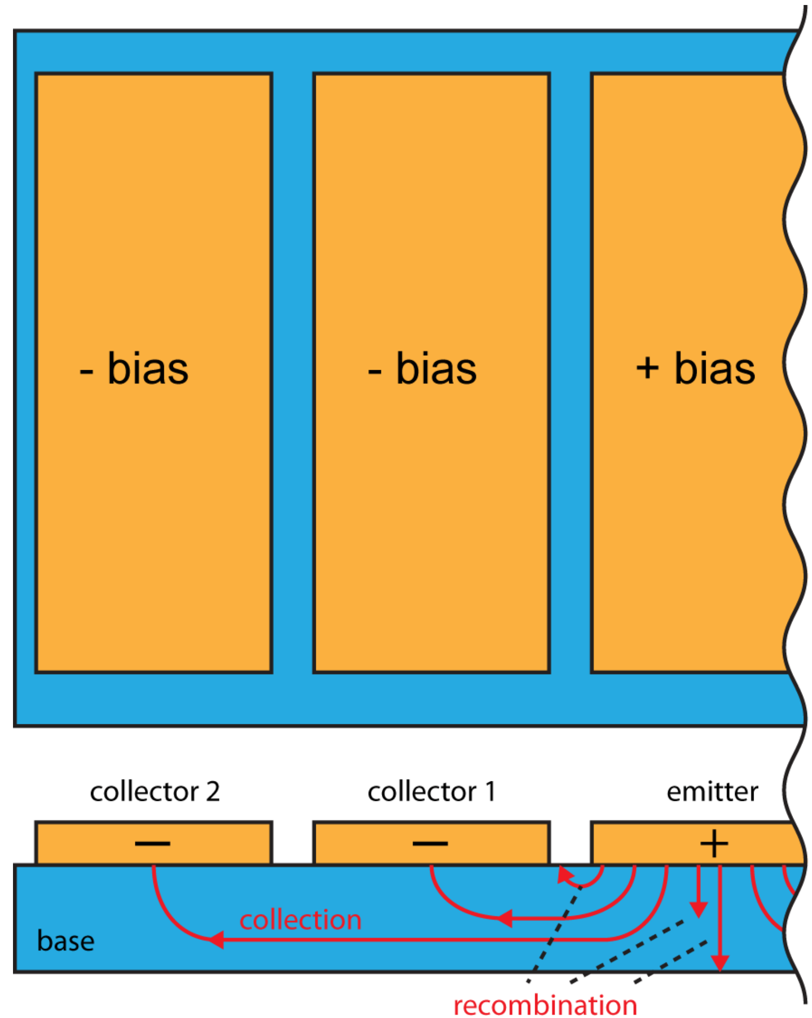
Areal J_{Dark} ~2× higher than square devices
- Consequence of plasma processing?

Perimeter J_{Dark} ~0.5× square devices
- Guarded devices
- "True" edge leakage current
- Minimum at bias where doping spike depleted

$(E_g^{InGaAs} / 2) < E_A(J_{Dark,Areal}) < E_g^{InGaAs}$

Hole injection in forward-biased linear devices





Forward bias highly favors hole injection

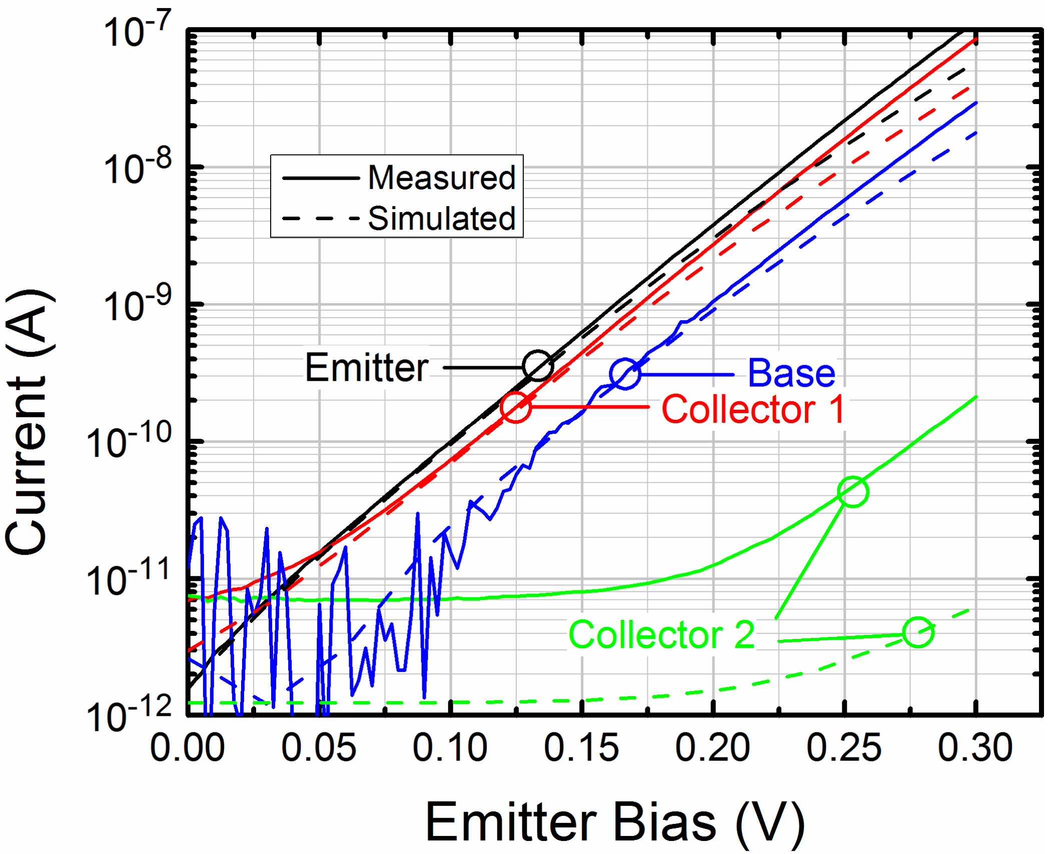
- Approximates photogeneration

Adjacent fingers reverse biased

- Lateral bipolar transistor
- Model validation
- Diffusion length estimation

Hole injection/collection I-V

12.5 μm pitch linear array

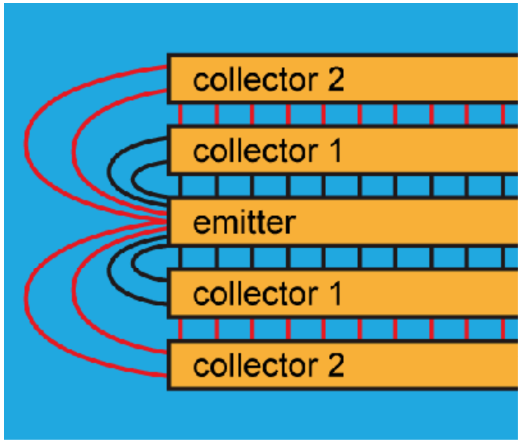


Hole collection efficiency $I_C/I_E=0.74$

- "Bipolar Gain" of 2.8
- Long hole diffusion length
- Interface recombination dominant

Model agreement

- Good for collection efficiency
- $I_E(V)$ good for $V \leq 0.15$ V
- Underestimates collector 2 current
  - Fringing?



Hole lateral collection and diffusion lengths

From simulation

Diffusion length = $(\mu_p kT\tau_{InGaAs}/q)^{1/2}$ [μ_p = 300 cm^2/Vs]: 70 μm

Collection length from perimeter / area current analysis (J_{perim}/J_{areal}): 8 μm

Difference arises from strong influence of interface recombination

- "Effective" lateral diffusion length includes interface recombination

From square device perimeter / area analysis

Assuming no surface leakage component in 18 pA/cm perimeter current: 22 μm

Subtracting 9 pA/cm (seen in linear devices) for surface leakage: 11 μm

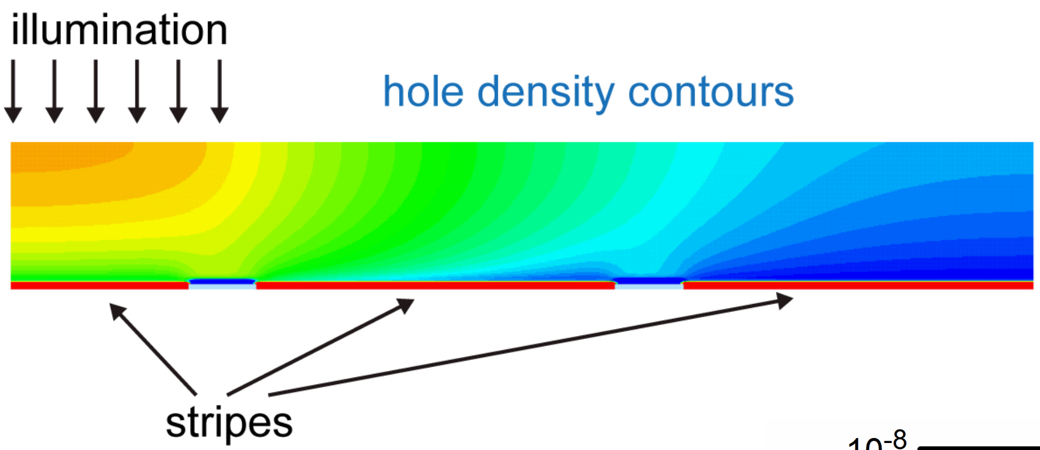
- Reasonable consistency with simulated perimeter / area analysis

Role of assumption of equal InGaAs electron and hole lifetimes

Relaxation of this constraint allows good model fits for variety of (τ_n, τ_p, IRV_p sets)

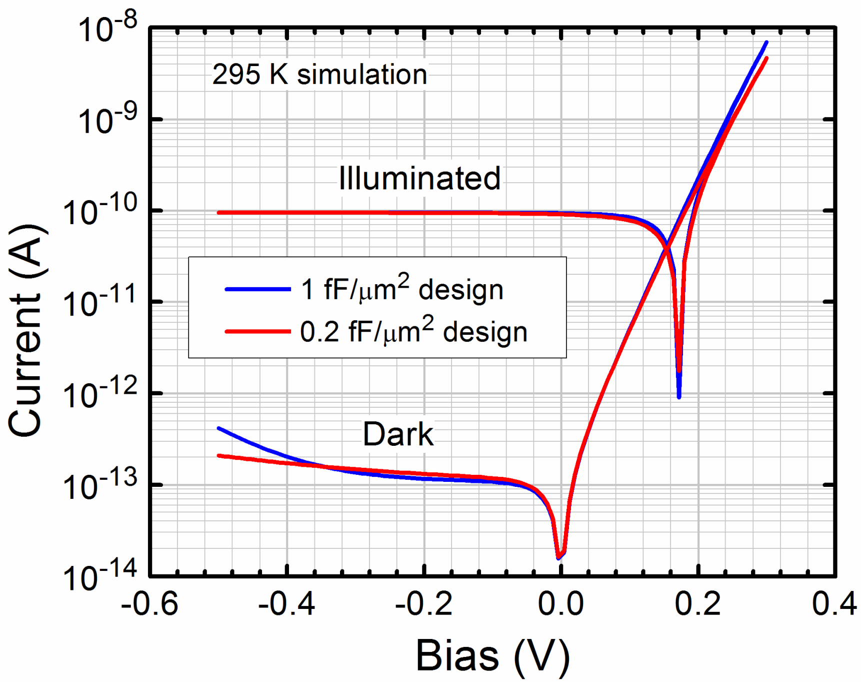
- Interface and bulk recombination not separable in thin absorbers
- Effective lateral diffusion length not sensitive to choice of these parameters
- Other absorber thicknesses required to determine IRV_p, but…
- $IRV_p = 0$ would imply $\tau_n / \tau_p \approx 200$ (τ_n = 20 μs, τ_p = 0.1 μs)

Application of simulation to design/analysis



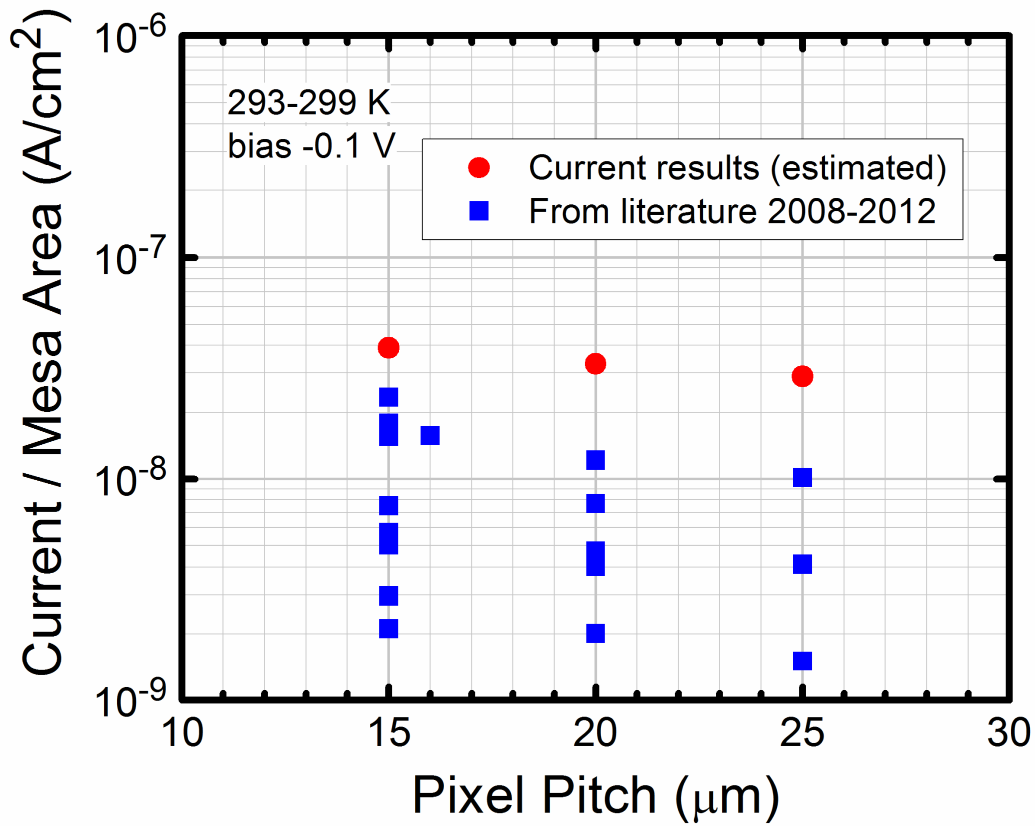
MTF simulation

Design flexibility



Comparison to state of the art

Estimates for FPA arrays
Derived from linear devices



Areas for further investigation

- Interface/bulk recombination
- Epitaxial material/design
- Plasma processes
- Dielectric quality

Conclusions

- Low dark current InGaAs detectors with simple mesa isolation demonstrated
- Areal dark current density 8-15 nA/cm2
  - Higher value may reflect plasma damage
- Perimeter dark current density 9-18 pA/cm
  - Higher value from lateral collection in unguarded devices
- Numerical model developed
  - Excellent fit to both reverse-bias and lateral bipolar transistor I-V
  - Dark current at large reverse bias dominated by generation in InAlGaAs
  - Lateral collection (~diffusion) length approximately 10 μm
  - Suggests significant interface recombination velocity
  - Useful for design optimization and performance prediction
- Small-pixel dark current estimate 2-20 × recent diffused devices
  - Many aspects of these devices not optimized