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Comparison of nBn and nBp mid-wave barrier infrared photodetectors

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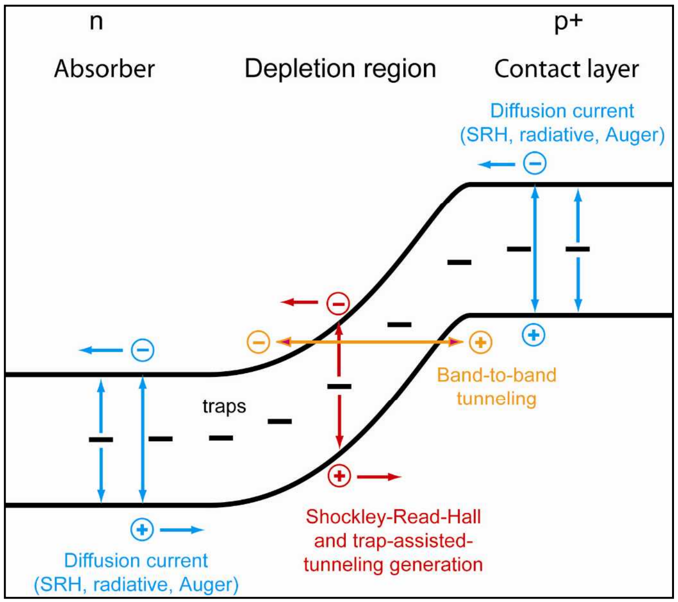
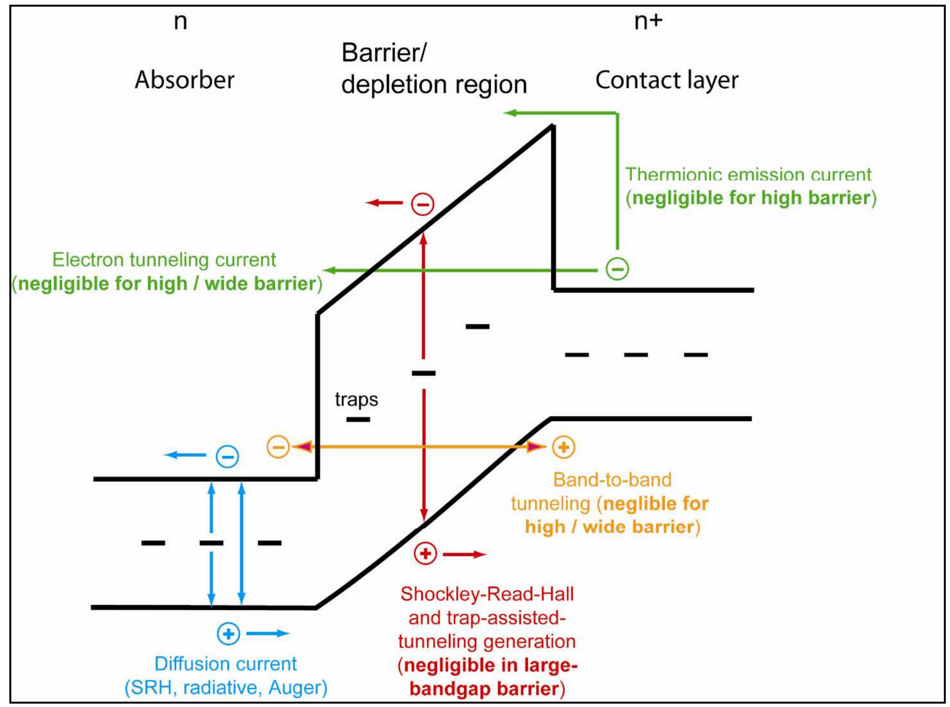
Intrinsic dark current sources in p-n and nBn detectors

Conventional p-n homojunction



Idealized nBn structure



- Idealized nBn structure eliminates dark current from all sources except generation processes that produce absorber diffusion current
- Elimination of depletion region SRH generation may greatly reduce dark current at lower temperatures (where depletion region SRH dominates in conventional p-n)

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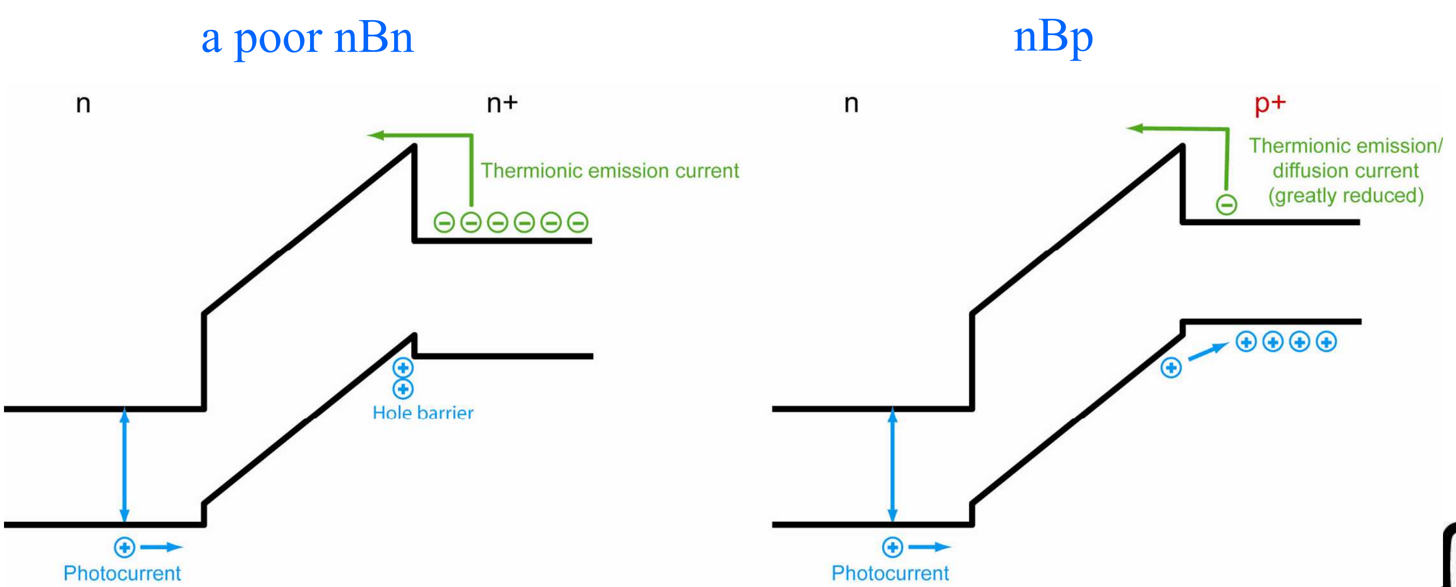
Why examine nBp structures?

nBn structure relies on a very special case with zero VB discontinuity and large CB discontinuity between absorber and barrier. In more general case:

- VB discontinuity produces undesirable hole barrier, or
- Smaller CB discontinuity (or high temperature) results in electron thermionic emission current

nBp structure allows substantially greater flexibility in material choices

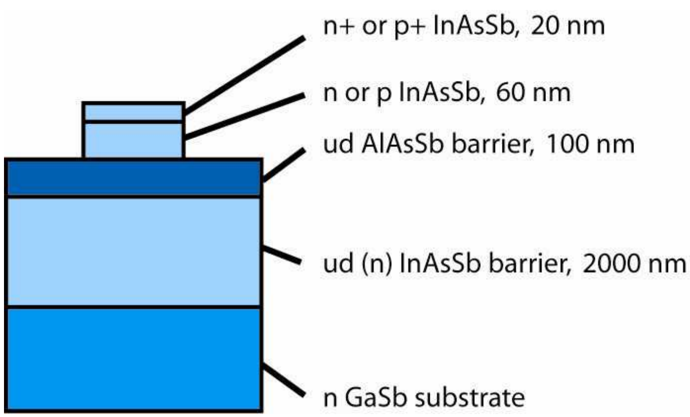
- p contact material need not be same as absorber
- p doping reduces thermionic emission dark current
- Also exhibits high responsivity at zero bias

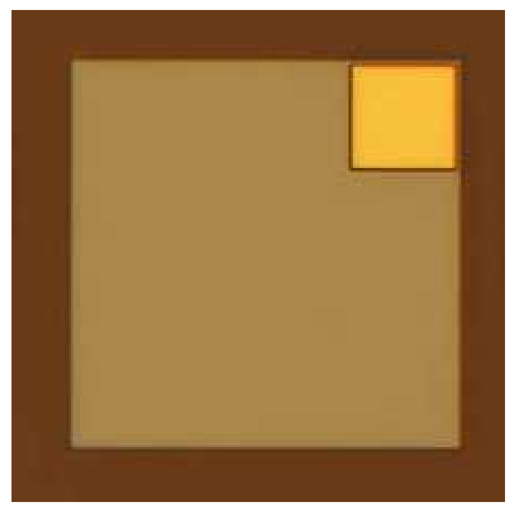


Goals and Methods

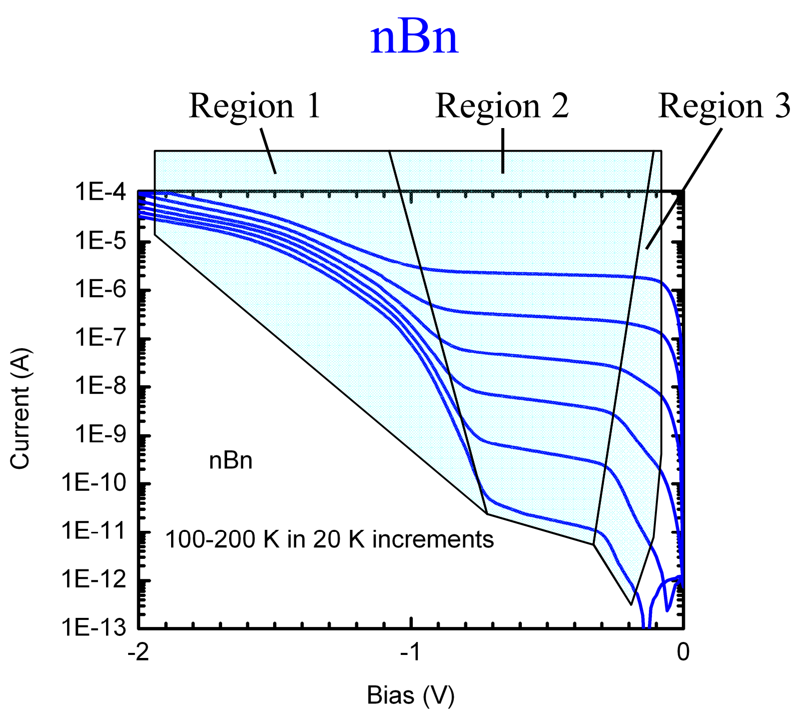
- Examine and compare characteristics of similar mid-wave nBn and nBp devices
  - Devices nominally identical except for doping of contact layer
- Perform numerical simulation to understand nBn and nBp performance
- Extract material properties relevant to device performance

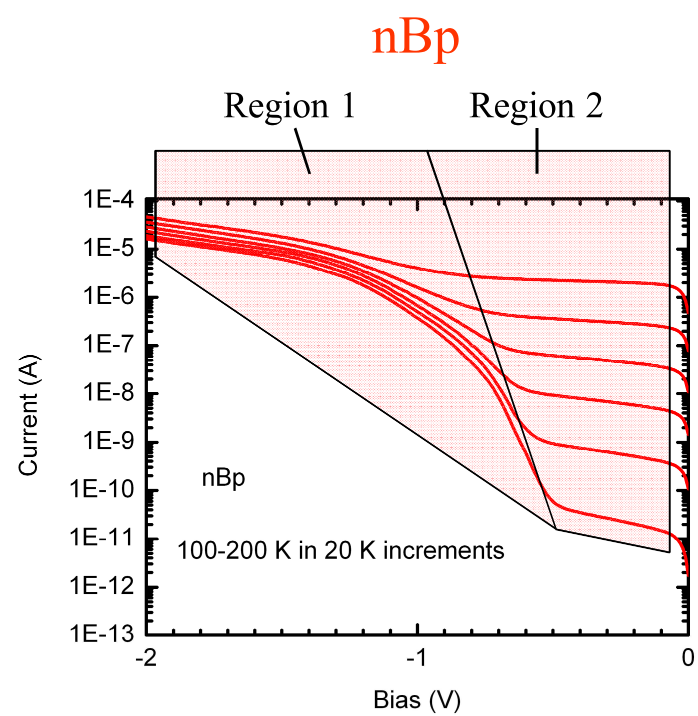
- Experimental comparison limited to unoptimized structures
  - *Changes to structures will significantly alter this comparison*
- Device structure
  - Absorber InAsSb nearly lattice-matched to GaSb, not intentionally doped
  - Barrier AlAsSb nearly lattice-matched to GaSb, not intentionally doped
  - Contact layer InAsSb, either Si-doped (nBn) or Be-doped (nBp)
  - Absorber bandgap ~ 4.2 µm (at 200 K)
  - Large-area devices (500 × 500 μm^2)





Detector dark I-V characteristics



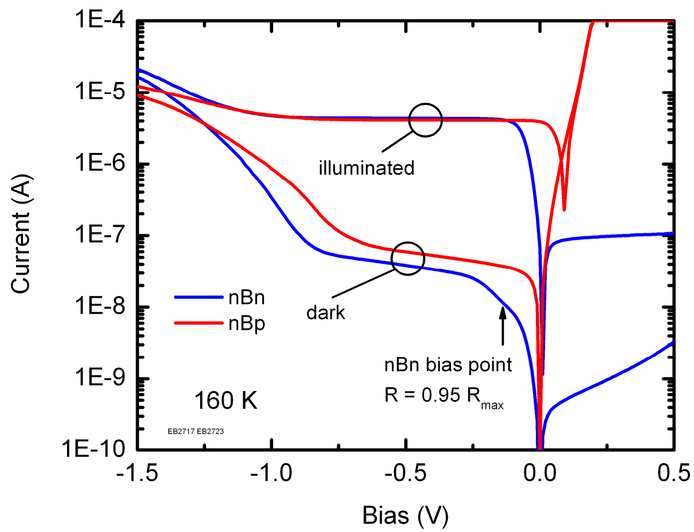


Region	T dependence	Bias dependence
1	weak	strong
2	strong	weak
3	strong	strong

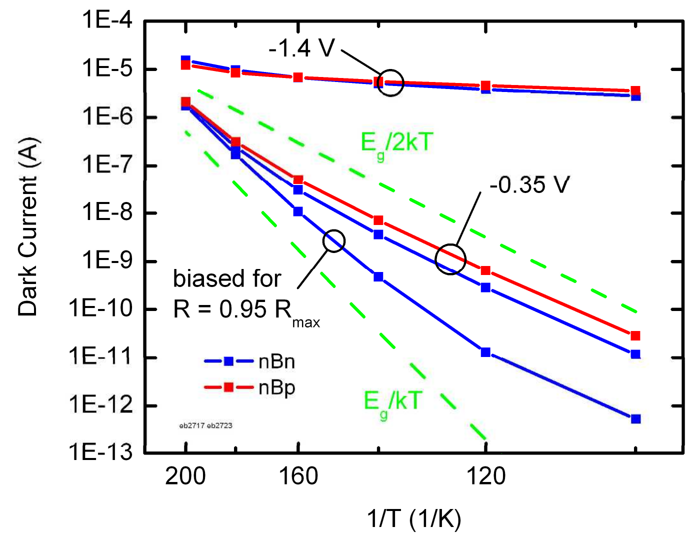
- nBn has nonzero I at zero bias (low T)
  absence in nBp suggests e- trapping
- nBp has no Region 3

Comparison of dark and illuminated I-Vs

I-V at 160 K



Dark I vs. T



"E_g/2kT" means ~ $T^{3/2} \exp(-E_g(T)/2kT)$

- nBp lacks Region 3 ("shoulder")
- Similar maximum responsivities
- nBn requires significant bias for max responsivity
- nBn dark currents generally slightly less than nBp
- nBn achieves max responsivity in shoulder region

- Region 1 has little temperature dependence
  → tunneling
- Region 2 has E_g/2kT dependence
  → depletion region Shockley-Read-Hall
- nBn biased at 0.95 R_{max} has E_g/kT dependence
  → diffusion current

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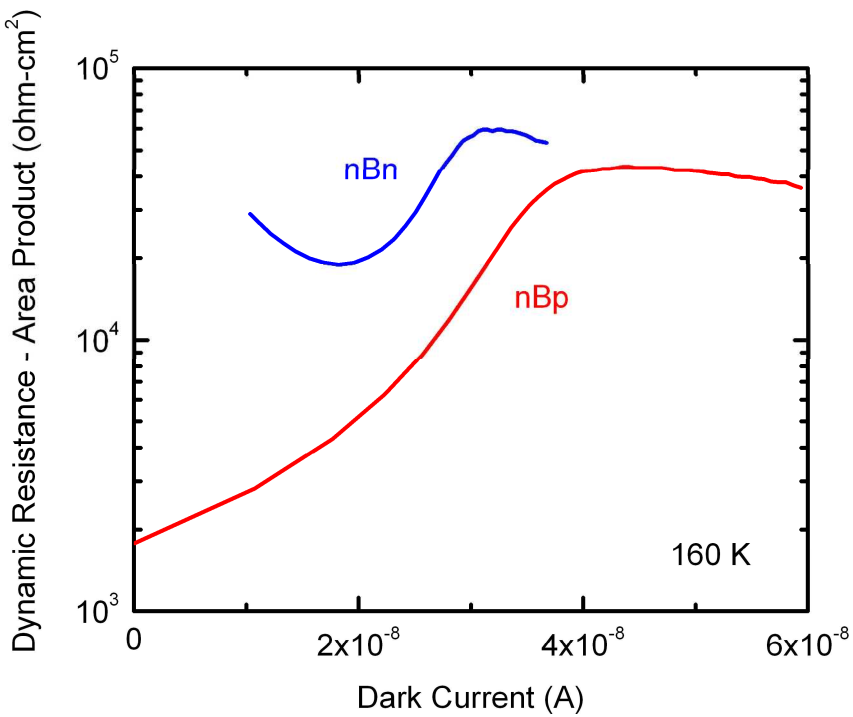
Comparison of dynamic resistance



Shown only for biases with responsivity ≥ 95% of maximum responsivity

For any given dark current, nBn has higher dynamic resistance

- Suggests that lower dark current of nBp at low bias offset by higher Johnson noise

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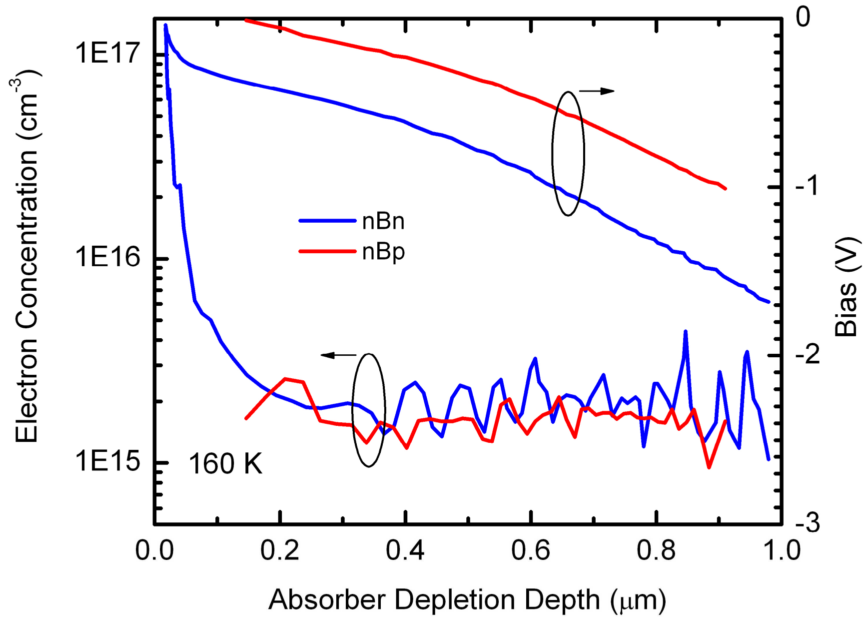
Capacitance-voltage measurements

$$c = \frac{c_{abs} c_{bar}}{c_{abs} + c_{bar}} \qquad n = -\frac{2}{A^2 q \varepsilon_0 \varepsilon_{abs}} \frac{dV}{d(1/c^2)}$$

- InAsSb absorber is n-type ~ 2×10^{15} cm^{-3}
- Zero-bias absorber depletion depths
  - nBn ~ 0 µm – **accumulation** layer
  - nBp 0.15 µm – large built-in potential
- Absorber depletion depths with bias -0.35 V
  - nBn 0.11 µm
  - nBp 0.51 µm



- nBn electron accumulation layer is depleted with bias ~0.3 V
  - Coincides with boundary between I-V regions 2 and 3
  - Suggests reduction of dark current in Region 3 related to existence of accumulation layer
- Existence of accumulation layer implies absence of depletion region SRH generation
- nBp has no accumulation layer because of larger built-in potential
  - nBp will have significant depletion region SRH at any reverse bias

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Finite element numerical analysis

- Commercial device simulator with temperature-dependent material parameters
- Drift-diffusion approximation, with thermionic barrier boundary conditions at higher T
- Generation/recombination mechanisms in absorber
  - Radiative
  - Shockley-Read-Hall
  - Trap-assisted tunneling (electric field enhancement to SRH)
  - Auger
- Generation/recombination assumed negligible in barrier
- Absorber/barrier VB discontinuity assumed to be zero
- Strain and quantum confinement effects ignored
- Doping as intended or as measured by C-V. Barrier assumed n-type 4×10^{15} cm^{-3}
- InAsSb SRH lifetime assumed to be 500 ns
- Contact minority carrier generation suppressed by including additional barriers
- Simulation restricted to |bias| < 0.6 V

Approximate expressions for dark current generation rates

In **neutral absorber**, where holes are strongly extracted by reverse bias

$(np << n_i^2 , and \; n >> n_i)$

$G_{SRH} = n_i^2 / (\tau_p n)$ (SRH)

$G_{Rad} = C_R n_i^2$ (Radiative)

$G_{Aug} = C_n n_i^2 n$ (Auger)

In **absorber depletion region**, where both holes and electrons are extracted

$(n << n_i$ and $p << n_i)$

$G_{SRH} = n_i / (\tau_p + \tau_n)$ (SRH)

$G_{Rad} = C_R n_i^2$ (Radiative)

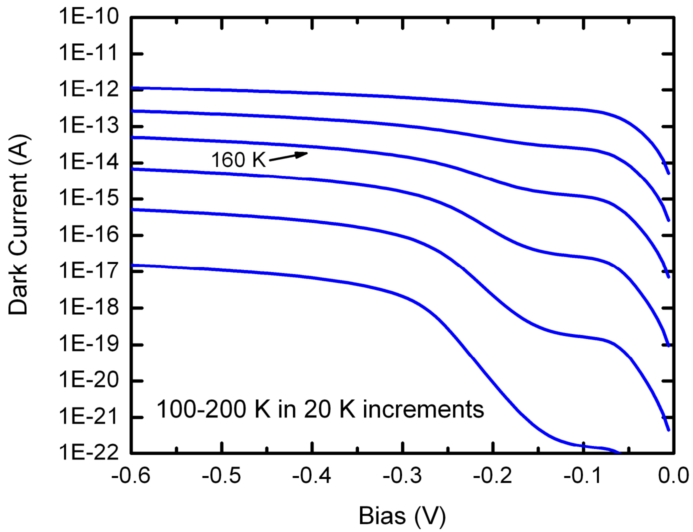
$G_{Aug} = 0$ (Auger)

SRH (either in neutral absorber or depletion region) dominates generation in these devices from 100-200 K

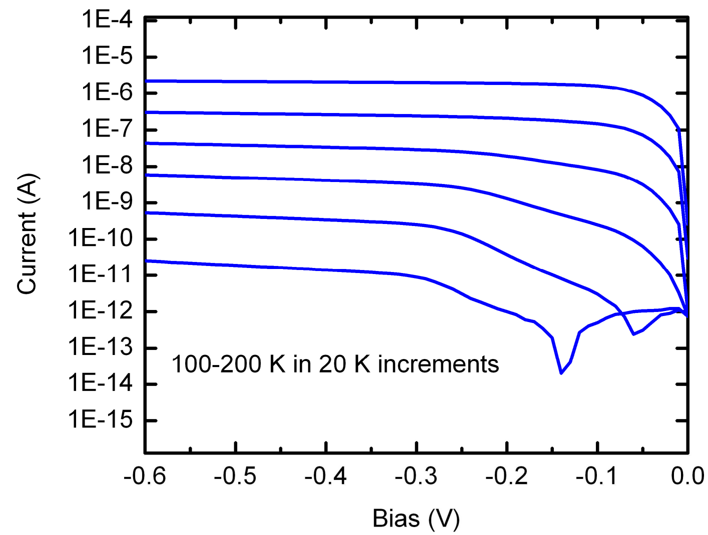
$$\frac{SRH_{depl}}{SRH_{neut}} \sim \frac{N_{abs}}{n_i} \frac{D_{depl}}{D_{neut}} \frac{\tau_p}{(\tau_p + \tau_n)}$$

Comparison of simulated and measured nBn characteristics

Simulated (1× 0.2 μm² device)



Measured (500×500 μm² device)



Differences between simulation and experiment may be due to

- Uncertainty in barrier doping and traps
- Residual absorber/barrier VB discontinuity
- Measurement current floor
- Uncertaintly in Auger and radiative coefficients (higher T)
- Temperature-dependent SRH lifetime

Depletion region SRH current implies SRH lifetime 600 ns

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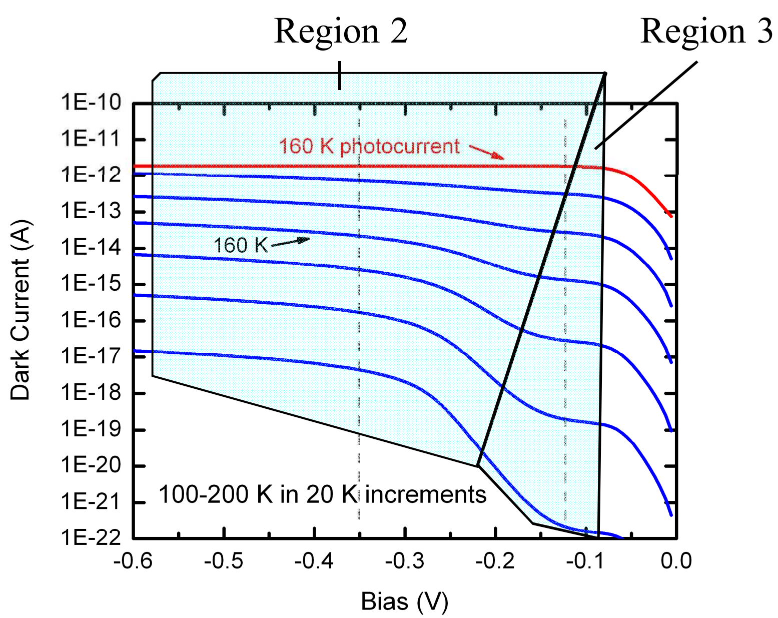
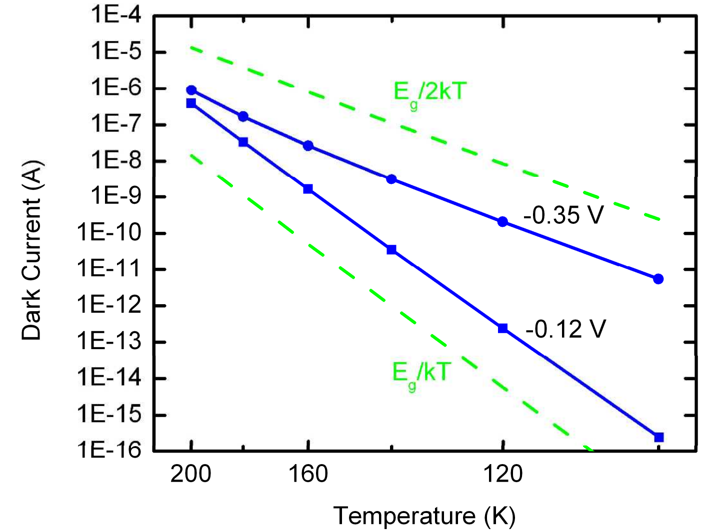
Simulated nBn dark current





Full responsivity is achieved in Region 3

Current plateaus in Region 3, in contrast to high slope in experiment

As in experimental devices, T dependence of dark current is bias-dependent

- Suggests that depletion-region SRH dominates at -0.35 V (Region 2)
- Neutral absorber SRH (diffusion current) dominates at -0.12 V (Region 3)

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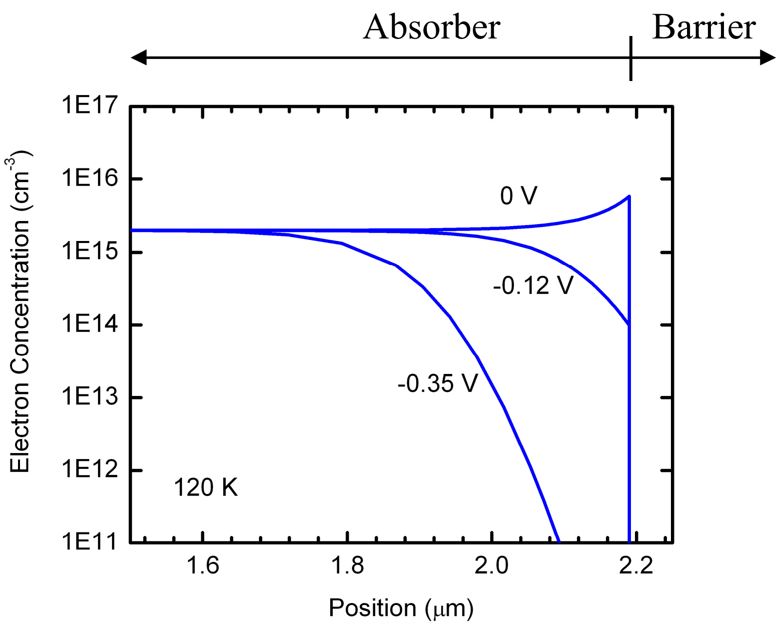
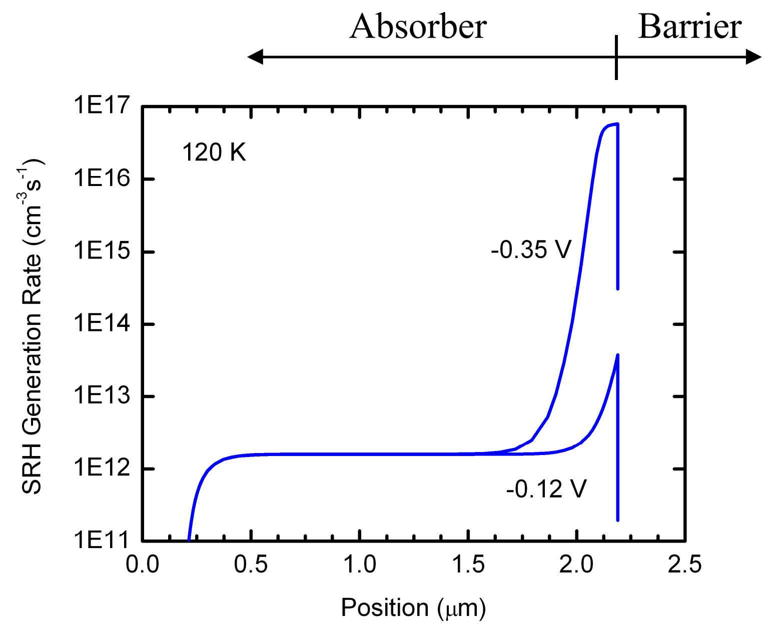
Spatial and bias dependence of nBn SRH generation rates





- Absorber accumulation layer exists at 0 bias
- Weak, thin depletion layer at -0.12 V
- Full, thin depletion layer at -0.35 V

- Depletion region SRH weak at -0.12 V
- Depletion region SRH rate saturates near -0.35 V

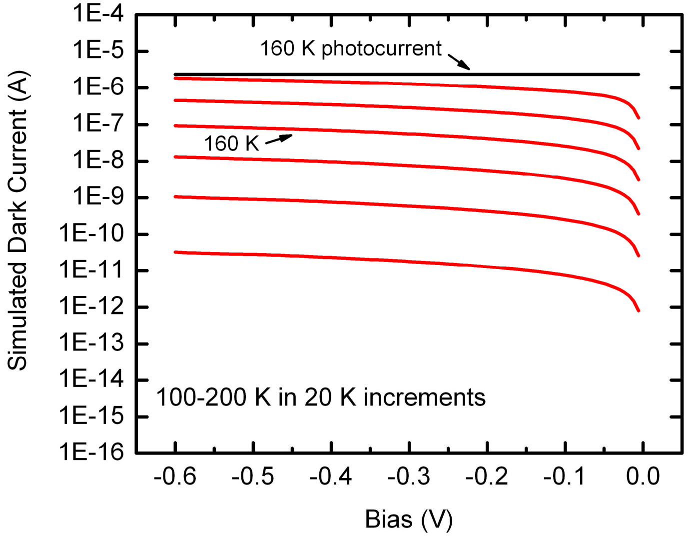
At bias of -0.12 V, which allows photocurrent collection, absorber has only weak depletion region

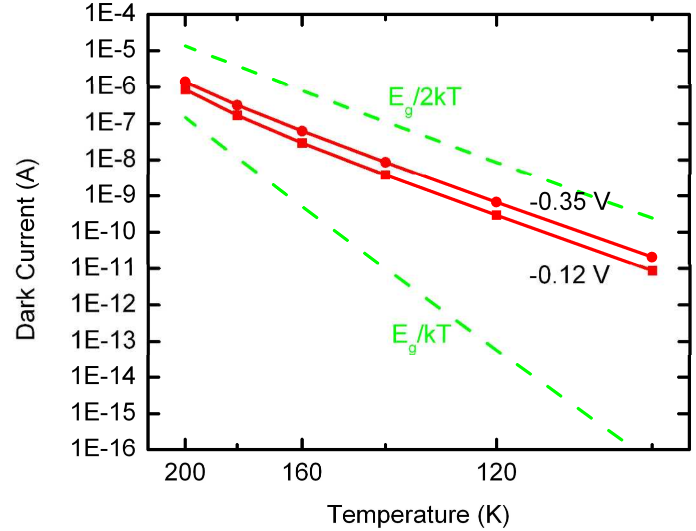
  – Dark current generation dominated by SRH (diffusion current) in neutral absorber region

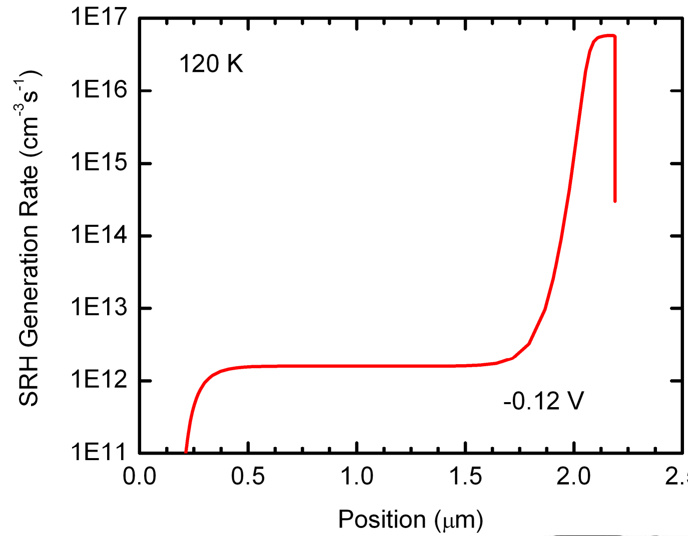
At bias of -0.35 V, a strong depletion region is formed

  – Depletion region SRH dominates

Simulated nBp dark current







Responsivity is flat across entire reverse bias range

– Equal to maximum nBn responsivity

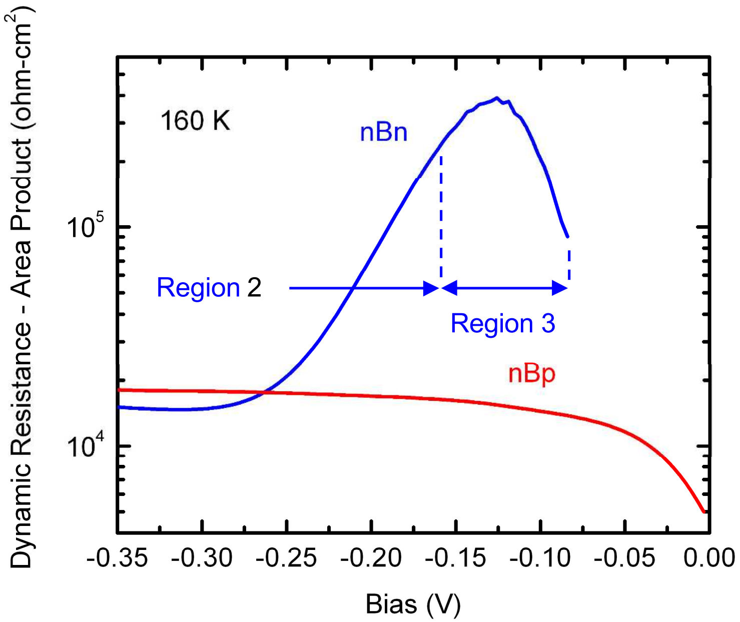
No "step" structure in I-V

T dependence is $E_g/2kT$ – like at both biases

Depletion region SRH at -0.12 V similar to nBn at -0.35 V

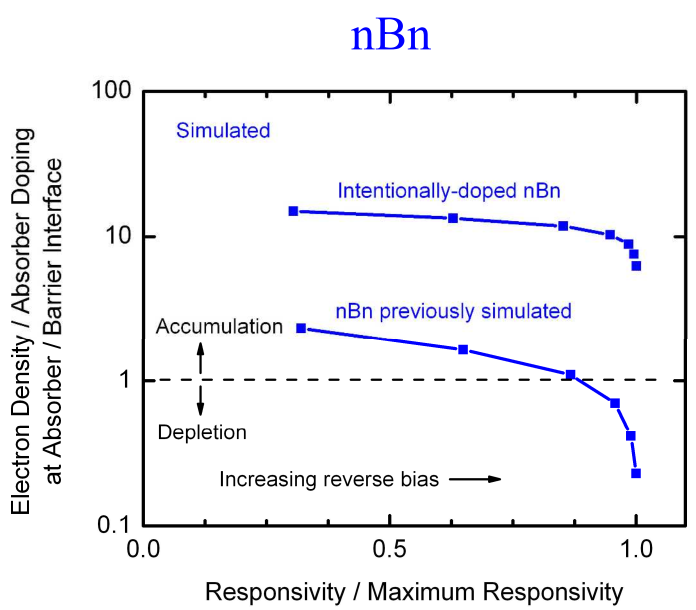
Characteristics very similar to simulated homojunction p-n

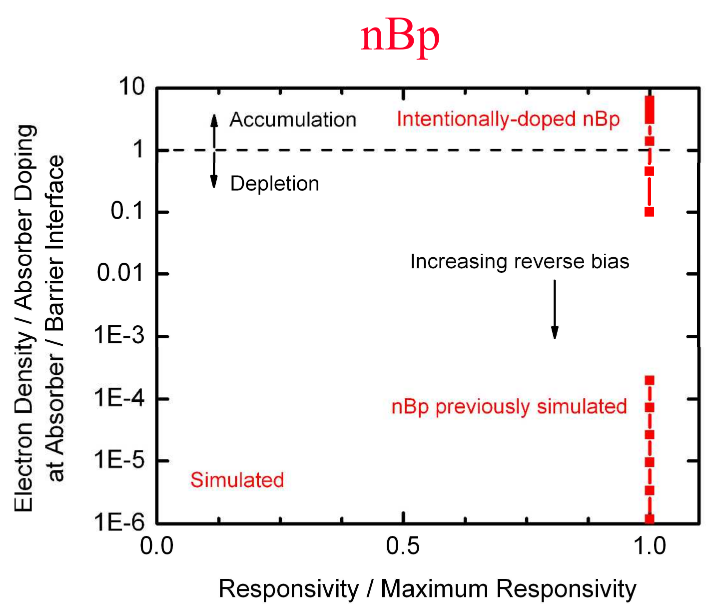
Comparison of simulated dynamic resistances



At best bias point nBn dynamic resistance is ~20x higher than nBp
High dynamic resistance of nBn obtained in Region 3 (diffusion-current-dominated)
Suggests that nBn is capable of having low Johnson noise

Can high responsivity be achieved with *no* absorber depletion?





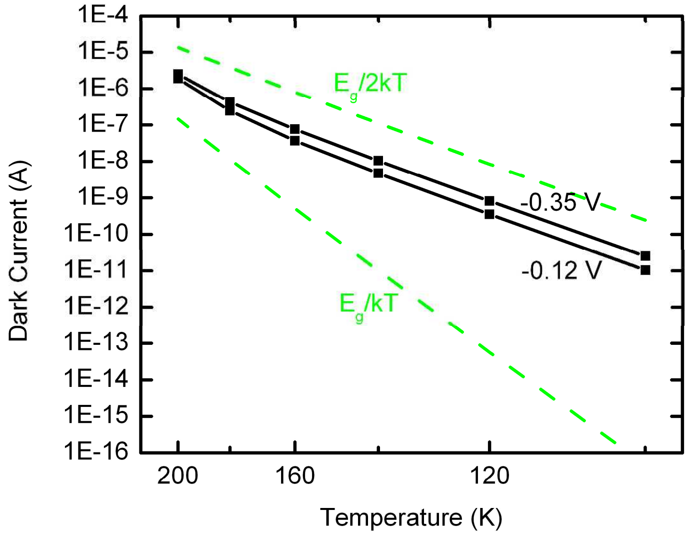
- With proper doping, high responsivity is possible in both nBn and nBp with no depletion
- Differential resistance of doped nBp comparable to nBn

→ **Performance of optimized nBp should be similar to optimized nBn**

Conclusions

- nBp structure is more generally applicable than nBn
- nBn and nBp mid-wave detectors fabricated with dark currents dominated by intrinsic sources (not sidewall leakage)
- Experimental characteristics of nBn and nBp qualitatively different
  - nBn exhibits bias region where diffusion current dominates at low T
  - nBp dark current dominated by depletion region SRH
- Simulation confirms observed behavior in both devices
- Characteristics of unoptimized nBp similar to convention p-n detector
- Differences in characteristics explained by larger nBp built-in potential
- Optimized nBn and nBp should have similar performance
  - Absence of parasitic sidewall conductance
  - Dark current dominated by absorber diffusion current

Simulated n-p homojunction dark current



Characteristics very similar to nBp – depletion region SRH dominates