Wigner Function Simulation of Intrinsic Oscillations, Hysteresis, and Bistability in Resonant Tunneling Diodes

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Outline

- Background
- Steady-State Simulations and Physics
- Transient Simulations and Physics
- Robustness of Physical Effects
- Conclusions

Electronic Device Simulation Models

Classical

$0 \leftarrow \hbar$

Quantum

Boltzmann Transport Equation

$$\frac{\partial f}{\partial t} = -\boldsymbol{v}\nabla_x f - \frac{\boldsymbol{F}}{\hbar}\nabla_k f + \left.\frac{\partial f}{\partial t}\right|_c$$

Wigner Function Transport Equation

MC

QMC

(moments)

$$\langle \phi \rangle n(x) = \int \phi(k) f(x,k) dk$$

(moments)

Hydrodynamic

$$\phi = 1, k, k^2 \rightarrow \frac{\partial n}{\partial t}, \frac{\partial n\boldsymbol{v}}{\partial t}, \frac{\partial nw}{\partial t}$$

Quantum Hydro

(first moment)

(first moment)

Drift-Diffusion

$$\frac{\partial n}{\partial t} = -\nabla \cdot (\mu n \nabla u + D \nabla n)$$

Density-Gradient

Wigner Function Model (1D)

Wigner function transport equation (WFTE):

$$\frac{\partial f(x,k,t)}{\partial t} = -\underbrace{\frac{\hbar k}{m}\frac{\partial f}{\partial x}}_{\text{diffusion}} - \underbrace{\frac{1}{\hbar}\int\frac{dk'}{2\pi}V(x,k-k')f(x,k')}_{\text{drift}} + \underbrace{\left[\frac{\partial f}{\partial t}\right]_{\text{c}}}_{\text{scatter}}$$

$$V(x,k) \equiv \int [U(x+y) - U(x-y)]\sin[2yk]dy$$

$$\left.\frac{\partial f}{\partial t}\right|_{\text{c}} = \frac{\hbar}{\tau}\left(\frac{f_{\text{eq}}}{n_{\text{eq}}}n - f\right)$$

Poisson equation to enforce self-consistency:

$$\frac{\partial}{\partial x}\left[\varepsilon(x)\frac{\partial}{\partial x}u(x)\right] = q\rho(x) = q^2[C(x) - c(x)]$$

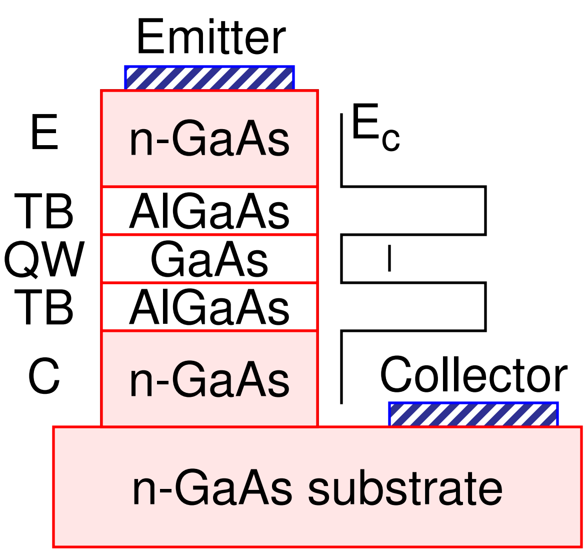
$$u(x) = U(x) - \delta U(x)$$

Charge and current density:

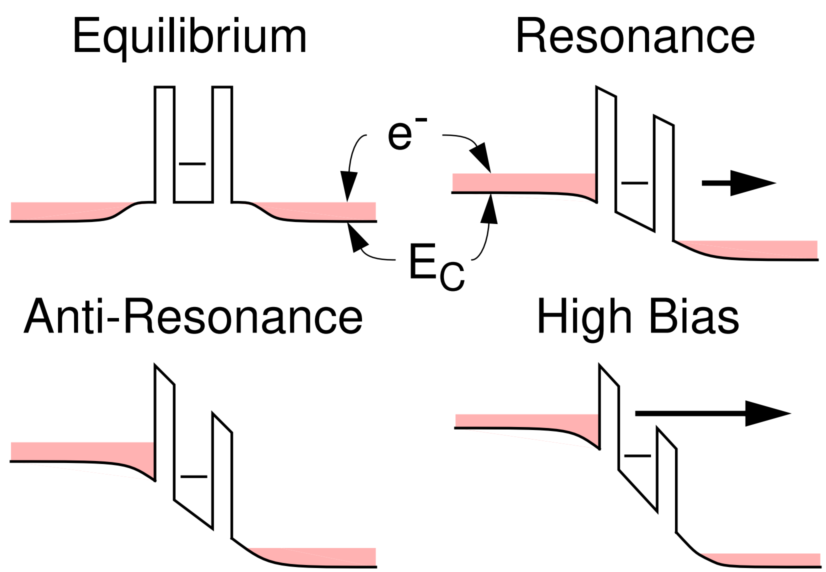
$$n(x,t) = \frac{1}{2\pi}\int f(x,k,t)dk \qquad J(x,t) = \frac{1}{2\pi}\int\frac{\hbar k}{m}f(x,k,t)dk$$

Resonant Tunneling Diode Basics

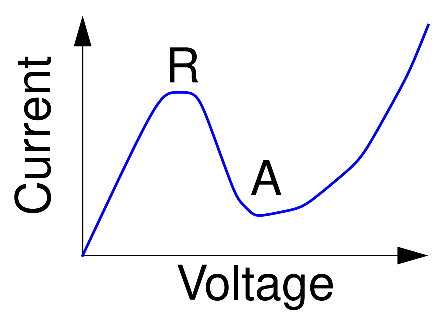
Basic RTD Structure



RTD Conduction Band Under Bias

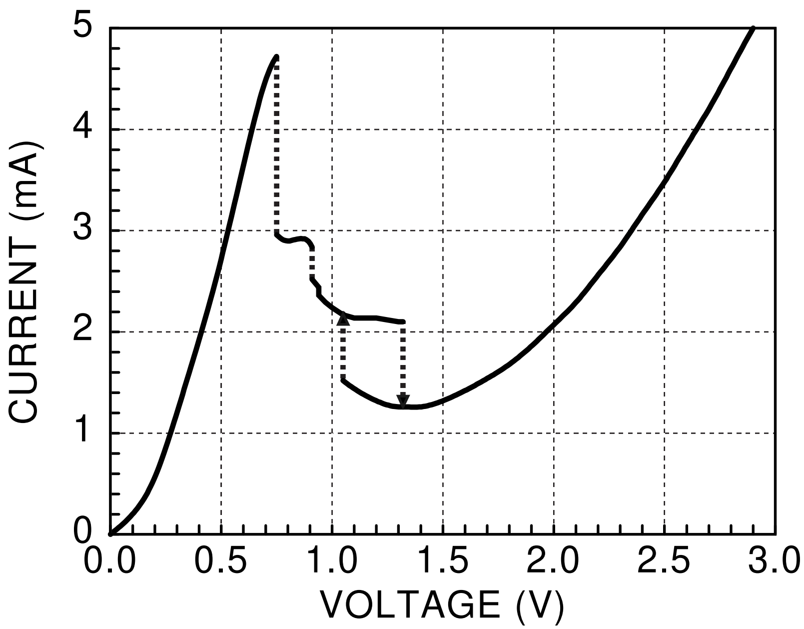


Current-Voltage Curve

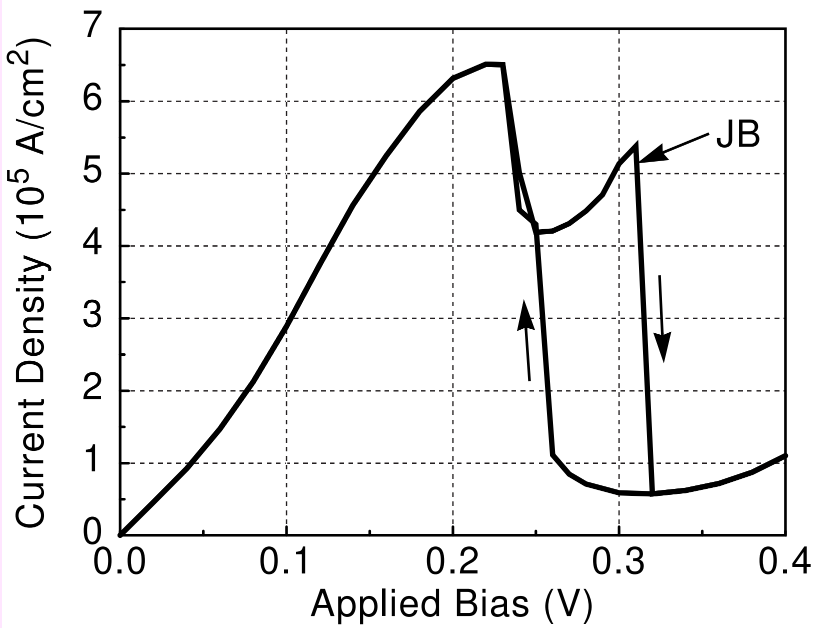


RTD Test and Simulation

Experimental RTD I-V Curve
[Brown et al., APL 55, 1777 (1989)]



WFM Simulated RTD I-V Curve
[Jensen and Buot, PRL 66, 1078 (1991)]



JB simulations first to produce typical RTD behavior:

- I-V plateau, hysteresis, unstable oscillations

This work examines device physics of JB RTD in detail

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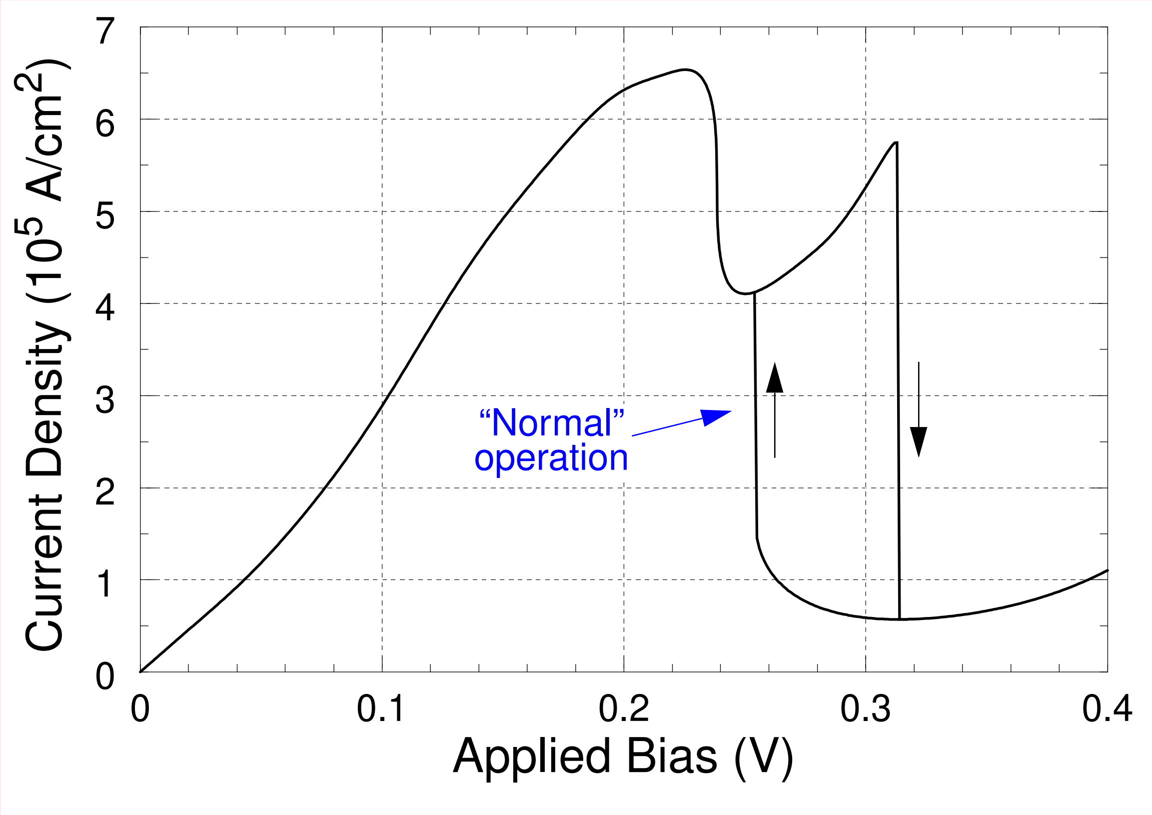
Steady-State I-V Curve

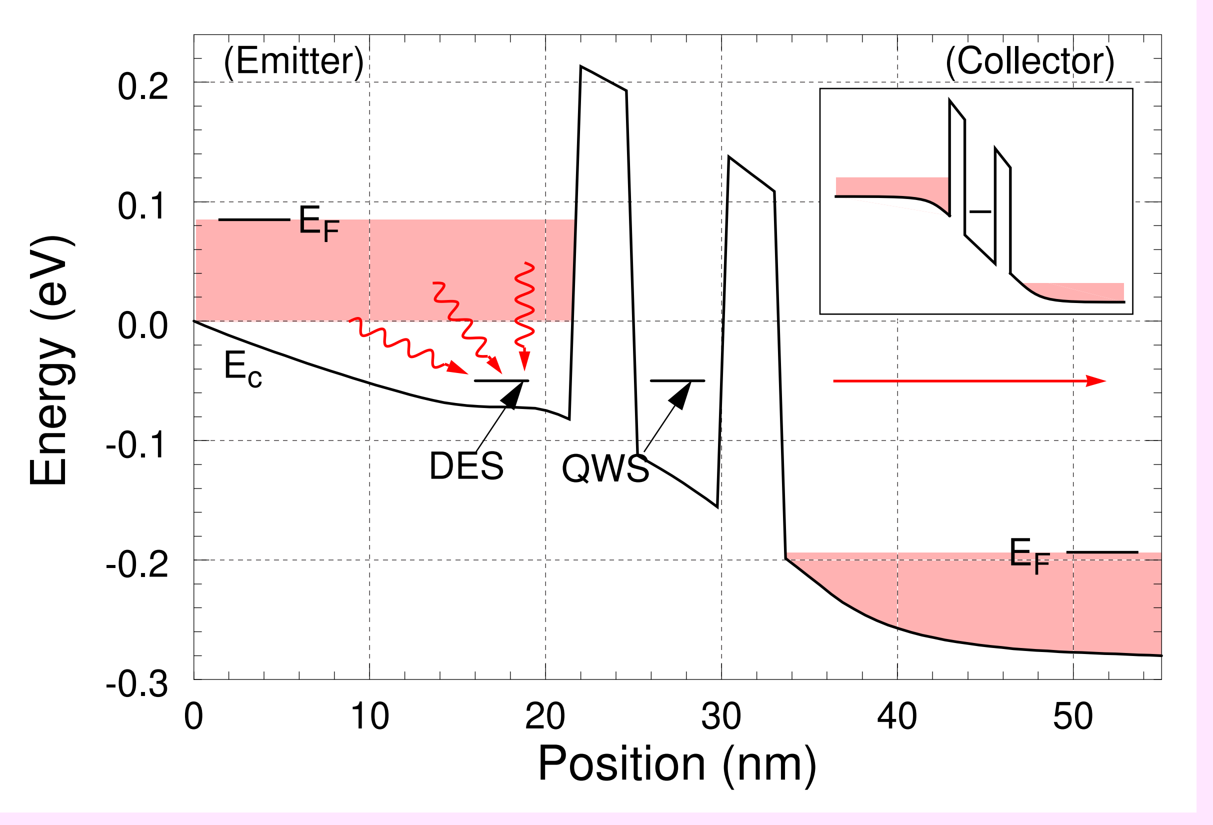


Discrepancy with experiment:

- Simulated plateau is steady-state effect
- Hysteresis normally seen below main peak

Applications: 3-state device, bistable device, analog function generator

Resonant Current Path in JB RTD

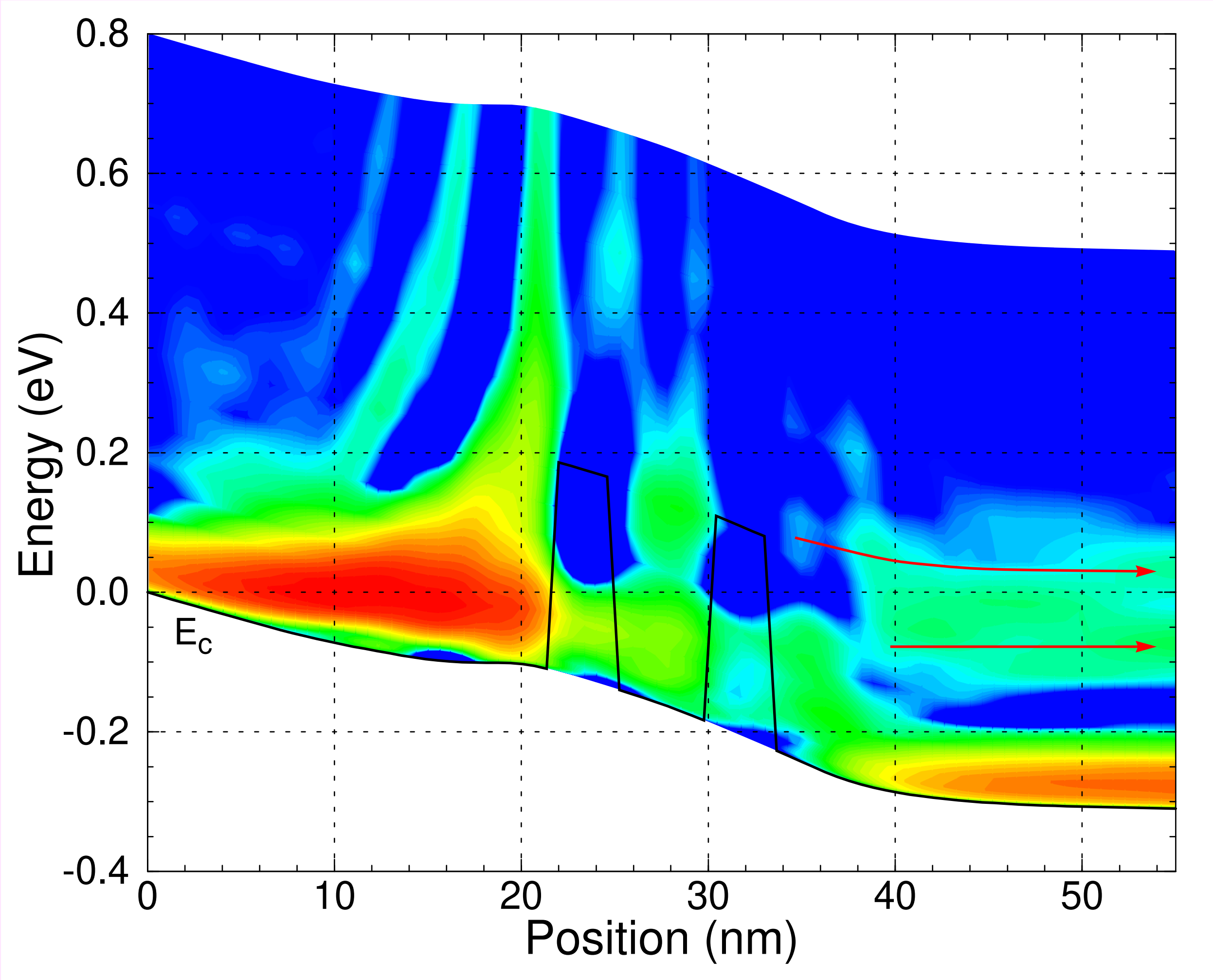


Plateau current due to transmission through discrete emitter state (DES)

Bistability due to charge storage in QW

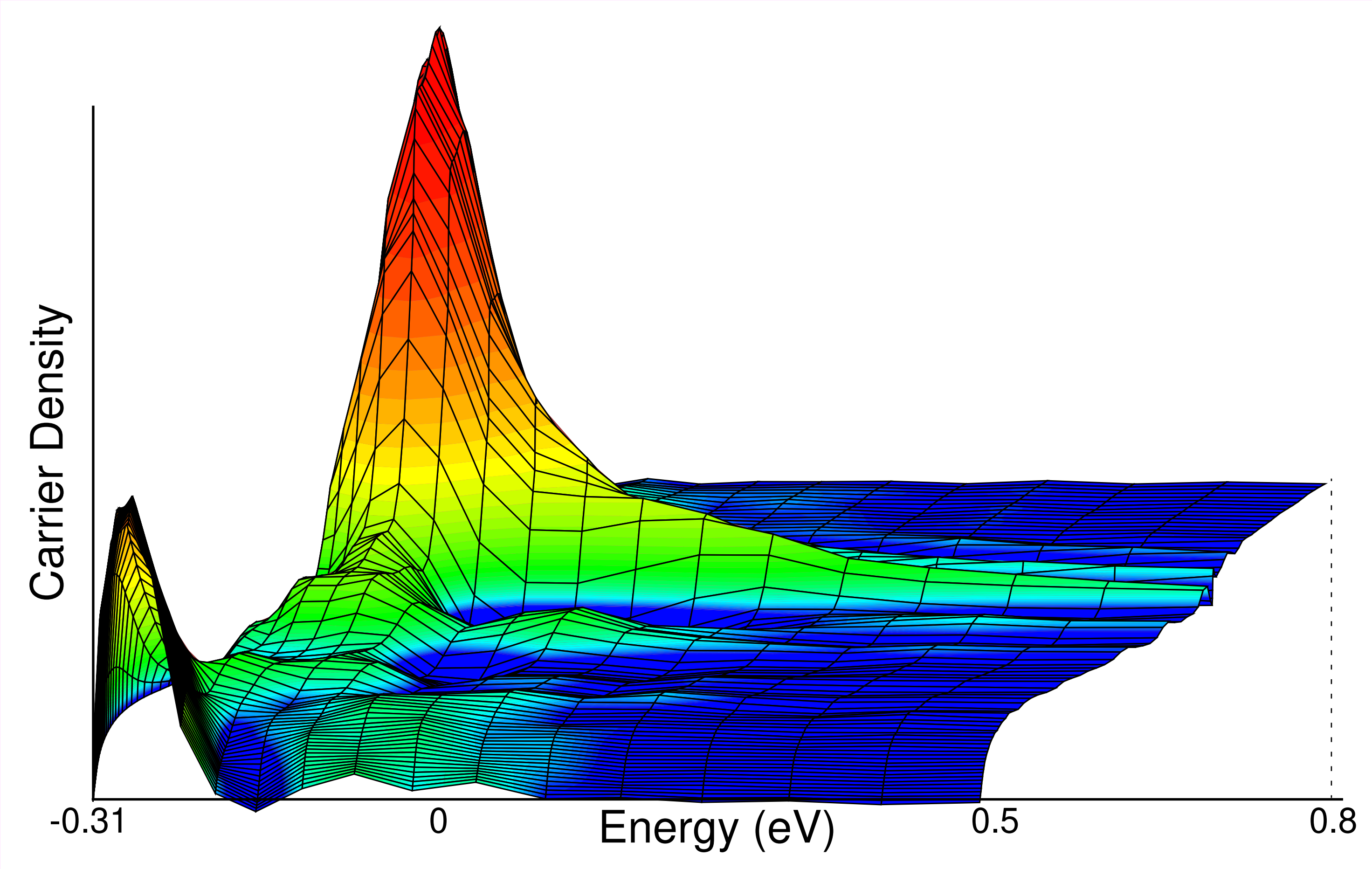
Plateau ends when DES forced above QWS

Carrier Density Contours (Plateau)



Current also from electrons transmitted over collector barrier

Carrier Density Contours (Plateau)



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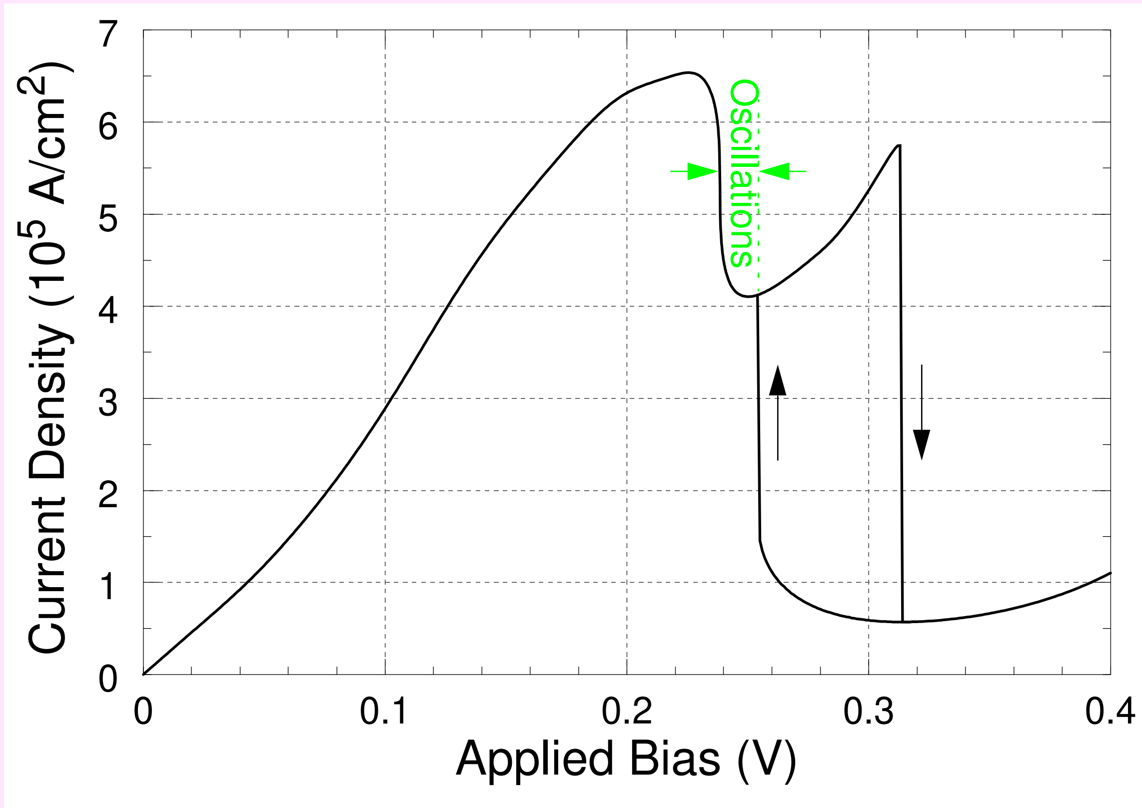
Transient I-V Curve Trace



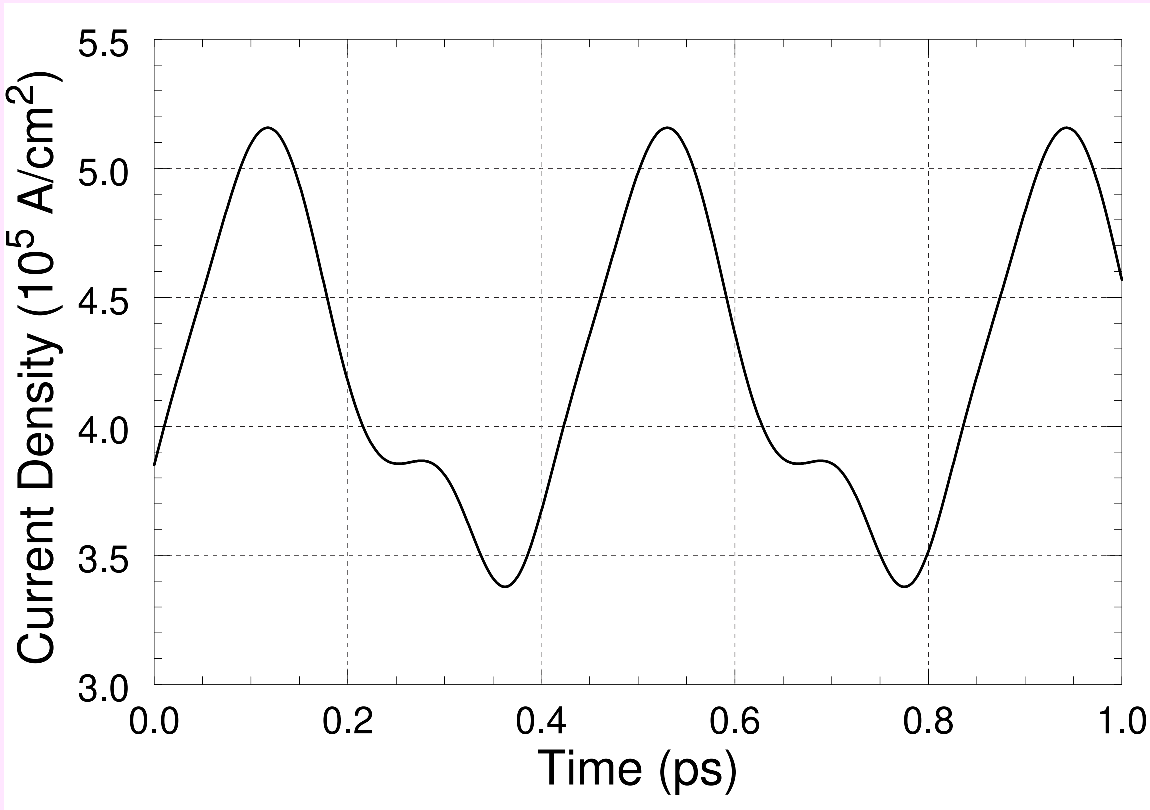
Virtually identical to steady-state I-V trace

Difference with experiment: Oscillations only in part of plateau

Applications: high-frequency oscillator, microwave detector

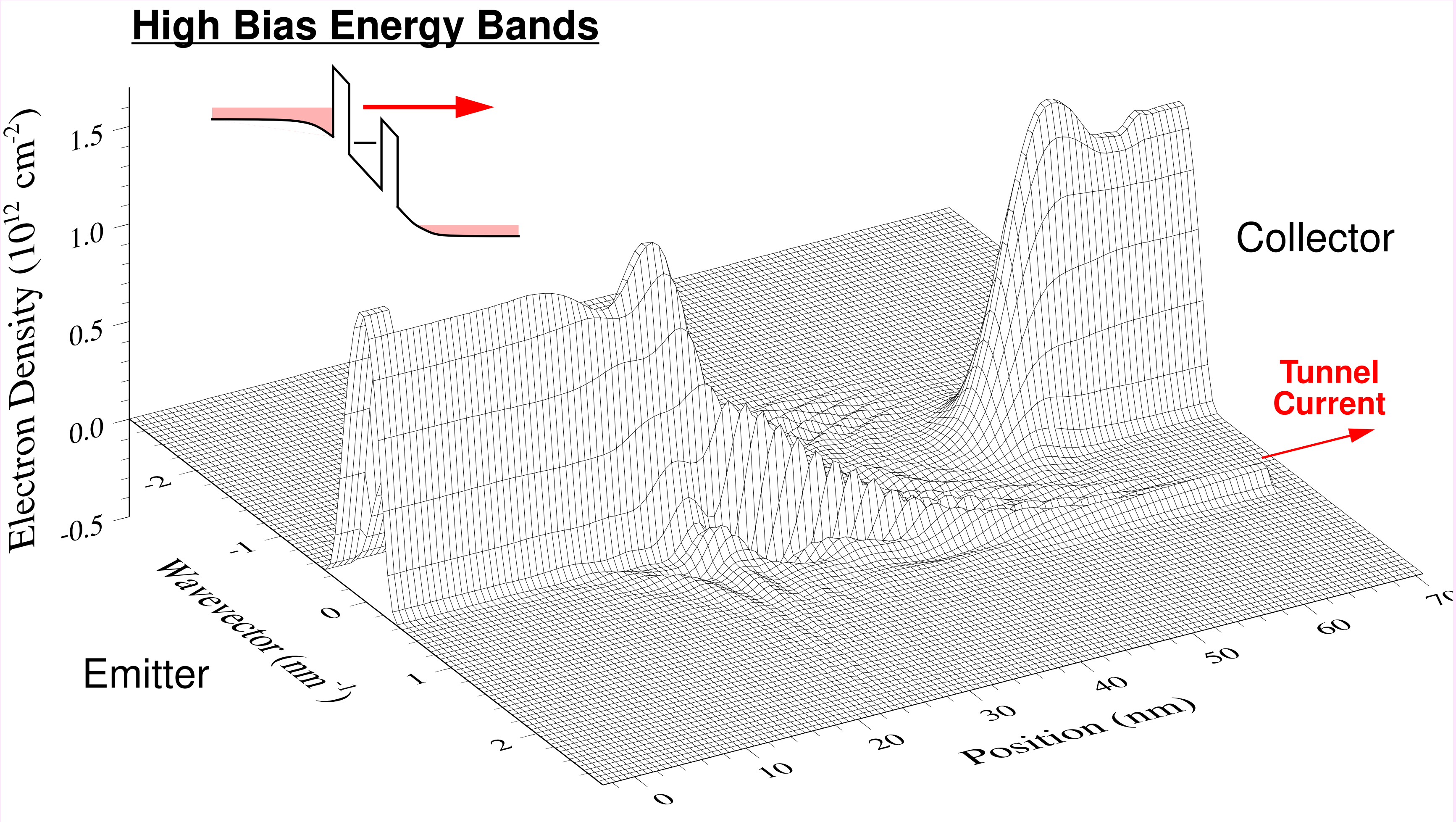
2.5 THz Current Oscillations

Device Current at 0.24 V Bias

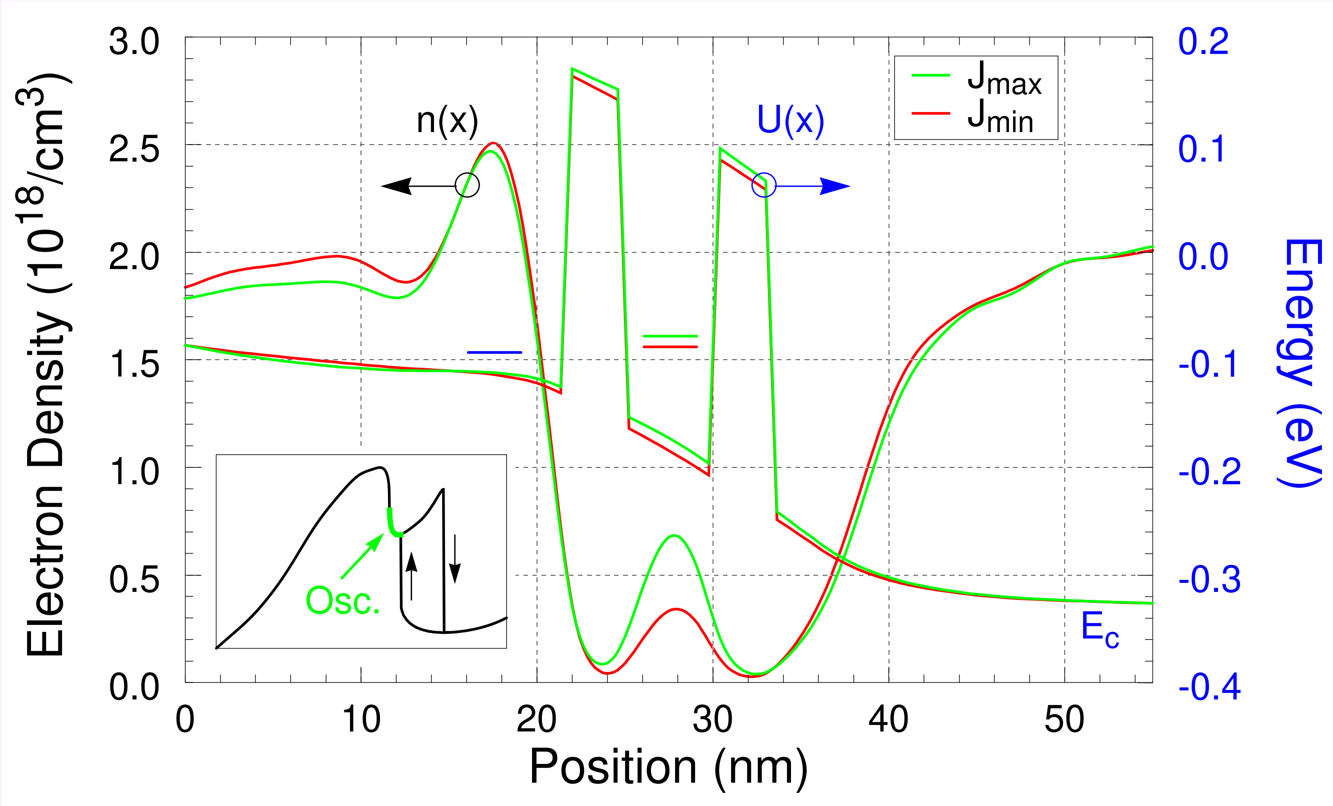


2.5 THz oscillations at fixed bias

Wigner Function Example: RTD at High Bias



Cause of Simulated Oscillations



Oscillations caused by temporal variation of DES/QWS alignment

Requires NDR for unstable operation

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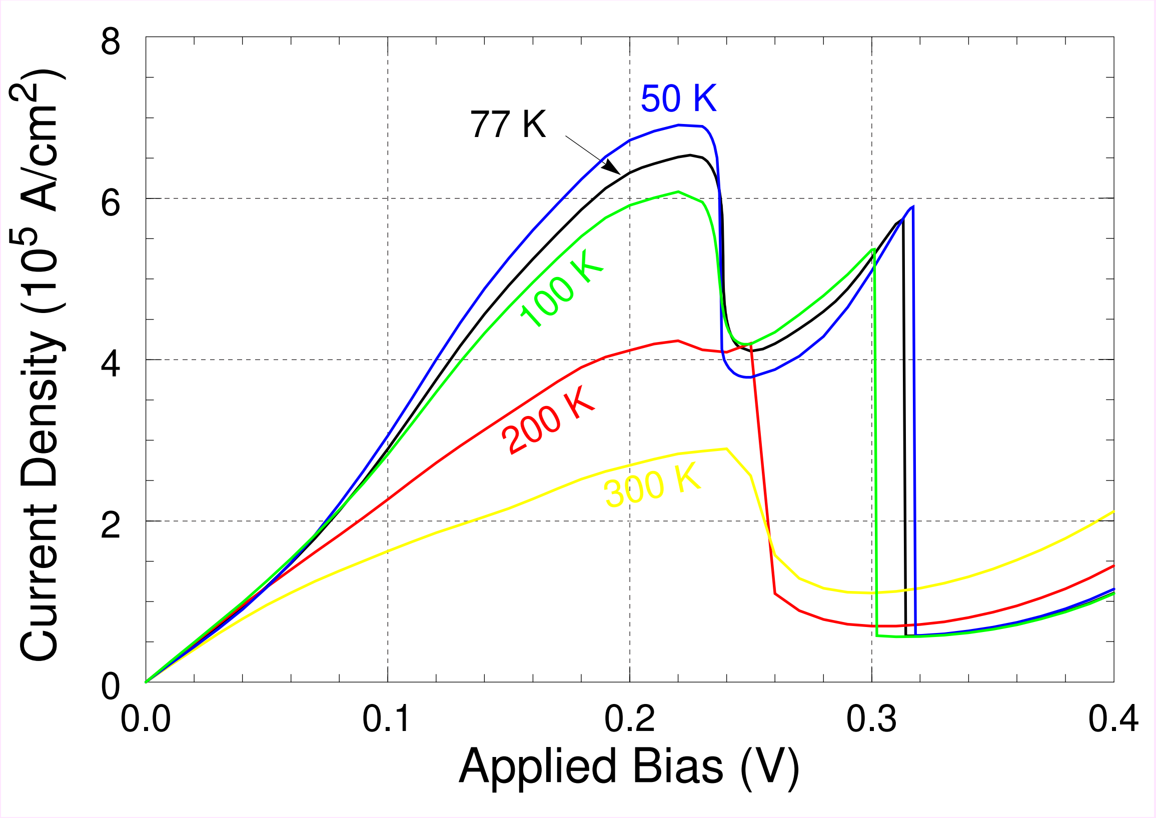
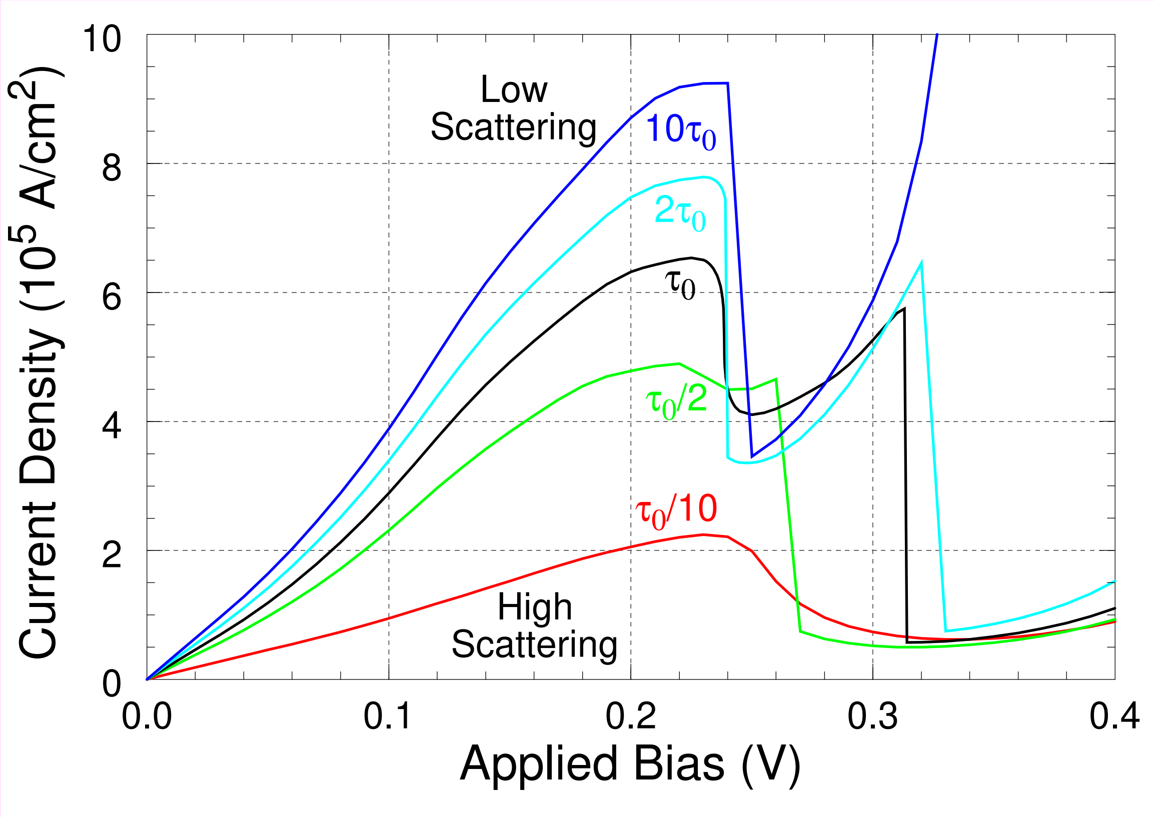
- **Robustness of Physical Effects**
    - **Sensitivity to scattering**
    - **Improved structures**
- Conclusions

Sensitivity to Temperature



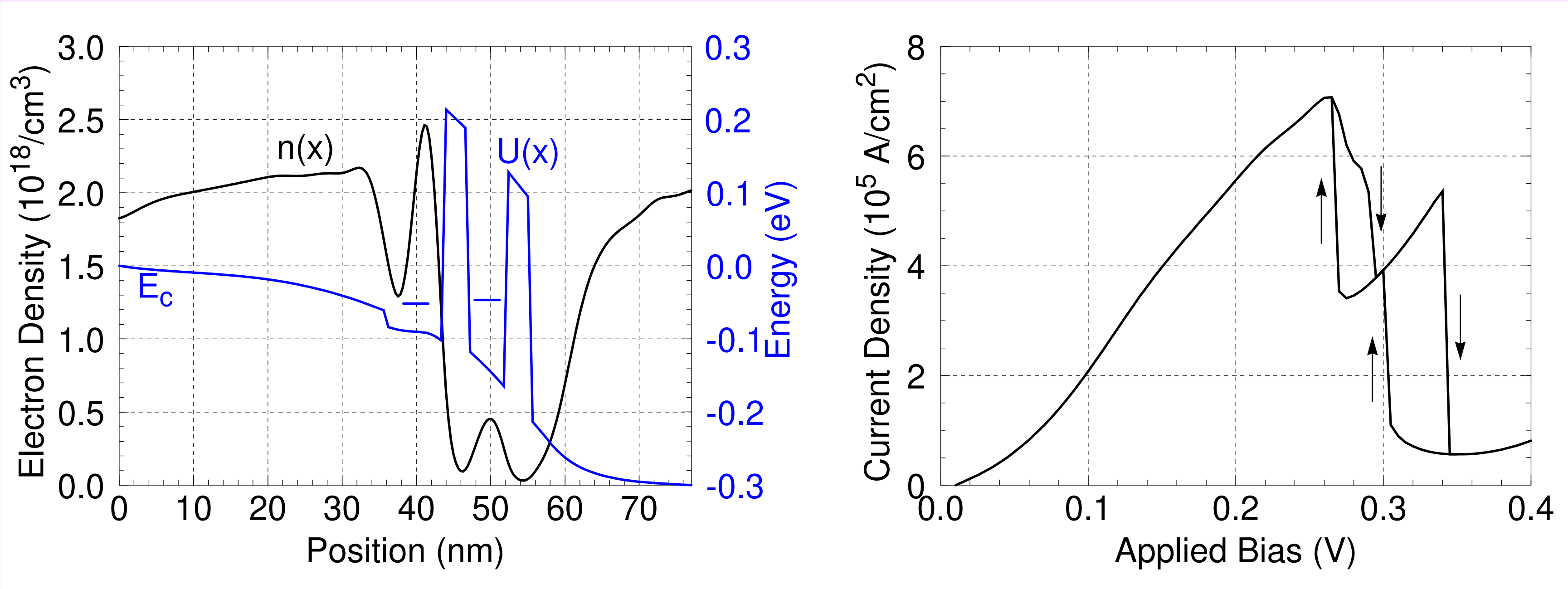
Plateau effects quenched above 200K

Sensitivity to Scattering Rate



Plateau effects destroyed at scattering time < $\tau_0/2$

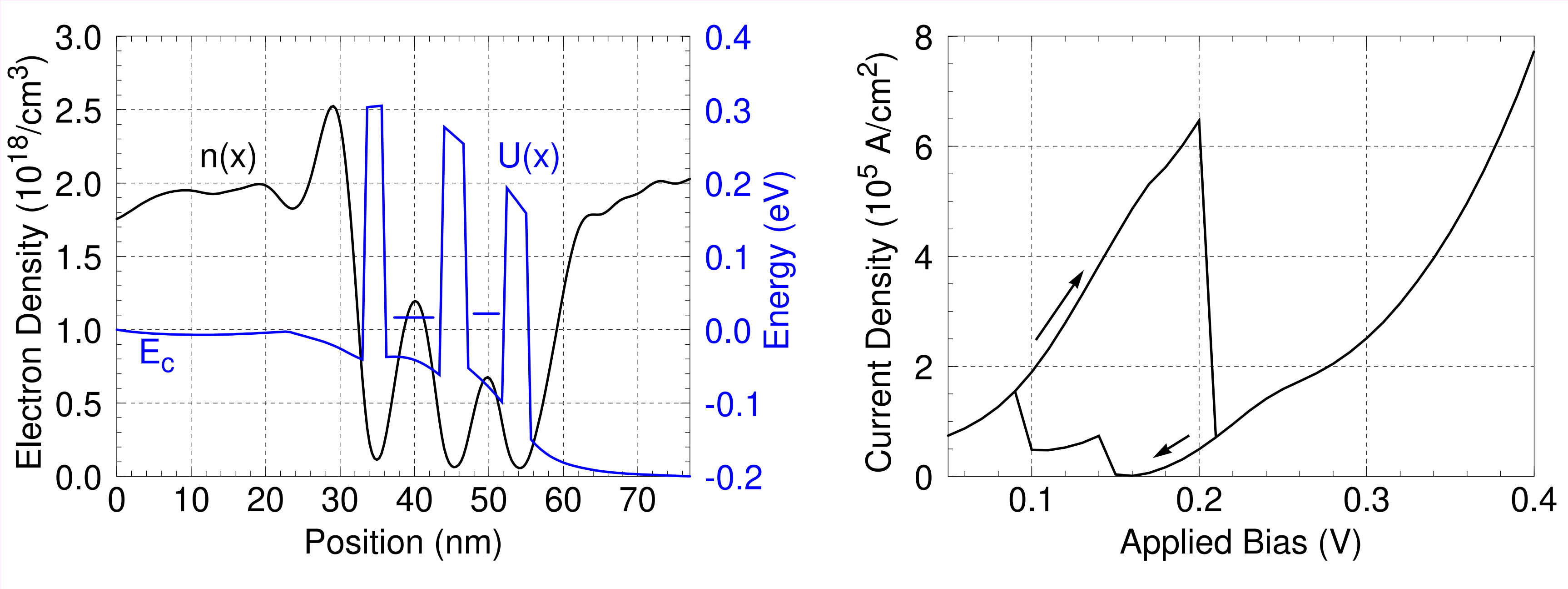
Modified RTD: Emitter QW



Bistability/hysteresis enhanced; oscillations lost

Robustness over temperature: little improvement

Modified RTD: Triple-Barrier



Plateau lost; Bistability/hysteresis enhanced; oscillations lost

Feature of JB RTD: DES appeared where no state had been

Conclusions

Physics of plateau feature in simulated I-V curve explained

- Not purely dynamic effect seen in experiment
- Requires scattering, aligned sharp energy levels
- Unstable oscillations also require NDR

Possible circuit applications suggested:

- 3-state device, bistable device, analog function generator
- high frequency oscillator/detector

Robustness analyzed: symbiosis of effects should be strengthened

Modified structures investigated: difficult to improve on JB RTD