NEMO1D: Motivation / History / Key Insights

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Thanks to:
NEMO Core Team Members

NEMO 1-D – 1994-1998
Roger Lake, Texas Instruments / UC Riverside
R. Chris Bowen, Texas Instruments / JPL / TI
Tim Boykin, U Alabama in Huntsville
Dan Blanks, Texas Instruments
William R. Frensley, UT Dallas

NEMO 1-D – 1998-2003
R. Chris Bowen, JPL
Tim Boykin, U Alabama in Huntsville

Post Docs / Students / Developers / Consultants:
Manhua Leng, Chenjing Fernando, Paul Sotirelis, Carlos Salazar-Lazaro,
Bill McMahon, Daniela Francovicchio, Mukund Swaminathan, Dejan Jovanovic

Experimentalists:
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Paul van der Wagt, Bobby Brar, Y. Chang (all TI), David Chow (HRL)

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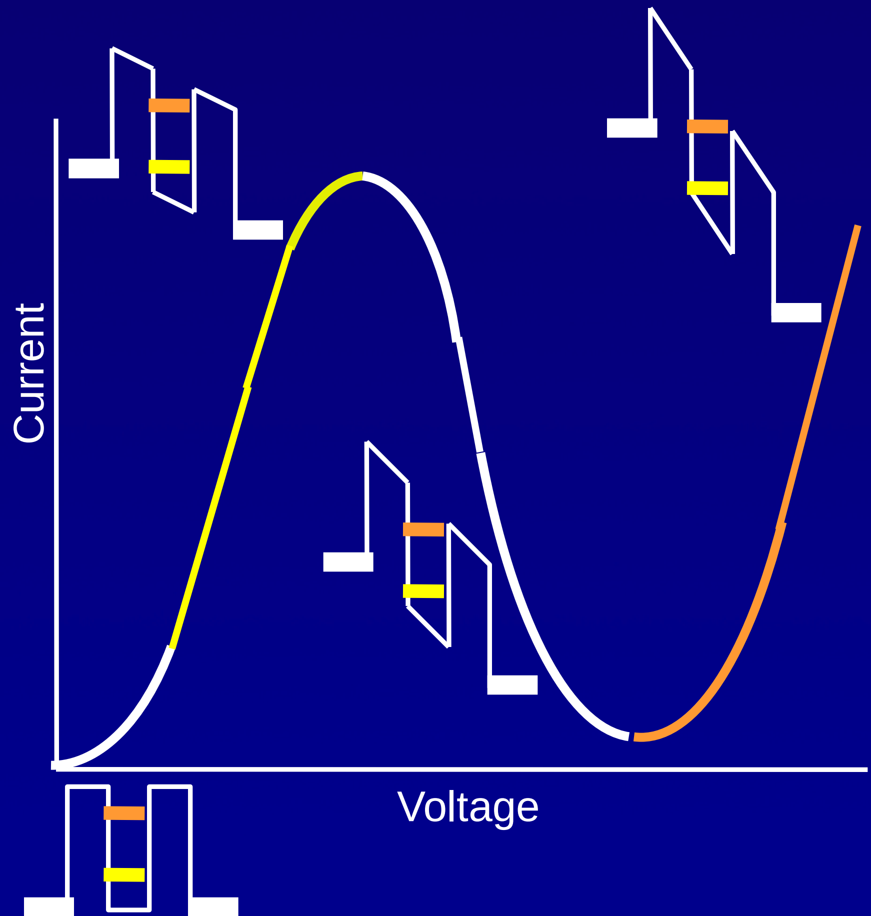
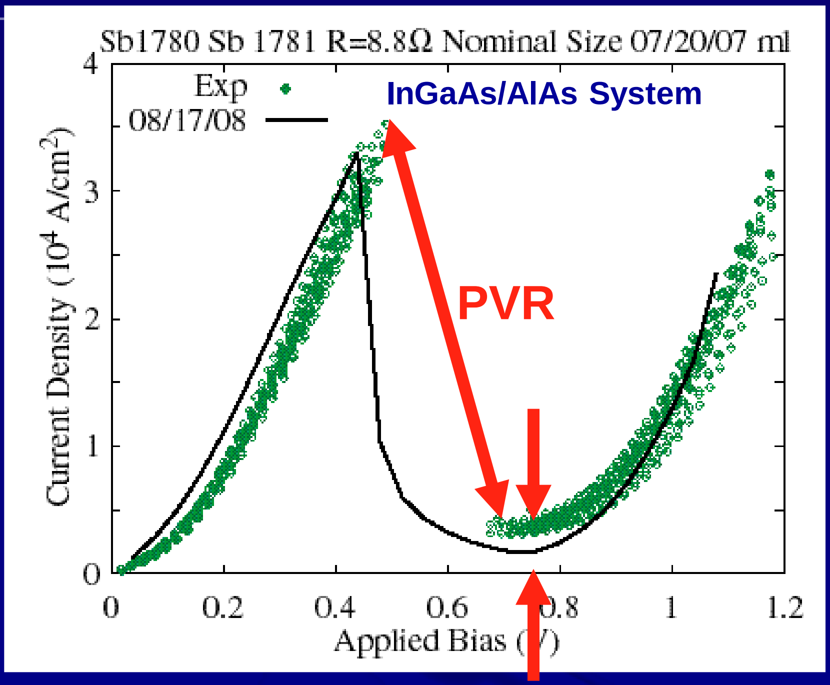
Basic Operation of a Resonant Tunneling Diode



Conduction band diagrams
for different voltages
and the resulting current flow



12 different I-V curves: 2 wafers, 3 mesa sizes, 2 bias directions

PVR – Peak-to-Valley-Ratio

1994: Best experiment PVR=80
=> On-Off-Ratio should to be >1,000

1994: What is the valley current physics?

1997: Can overlay experiment and theory.
What are the key insights?

NCN

Resonant Tunneling Diodes in 1994

Potential:

- THz operation – limited only by tunneling time
- NDR => fast oscillations
- NDR => stable latches, digital logic

Challenges:

- Valley current too high => high "off" state current
- No production-like experiments => repeatability issues
- No generally accepted device modeling theory

⇒**Nanoelectronic Modeling – NEMO**

⇒Software tool that:

- Quantitative modeling
- Predictive design
- Physics-based understanding

State-of-the-art RTD Modeling and Simulation Knowledge 1994

Knowledge / Availability:

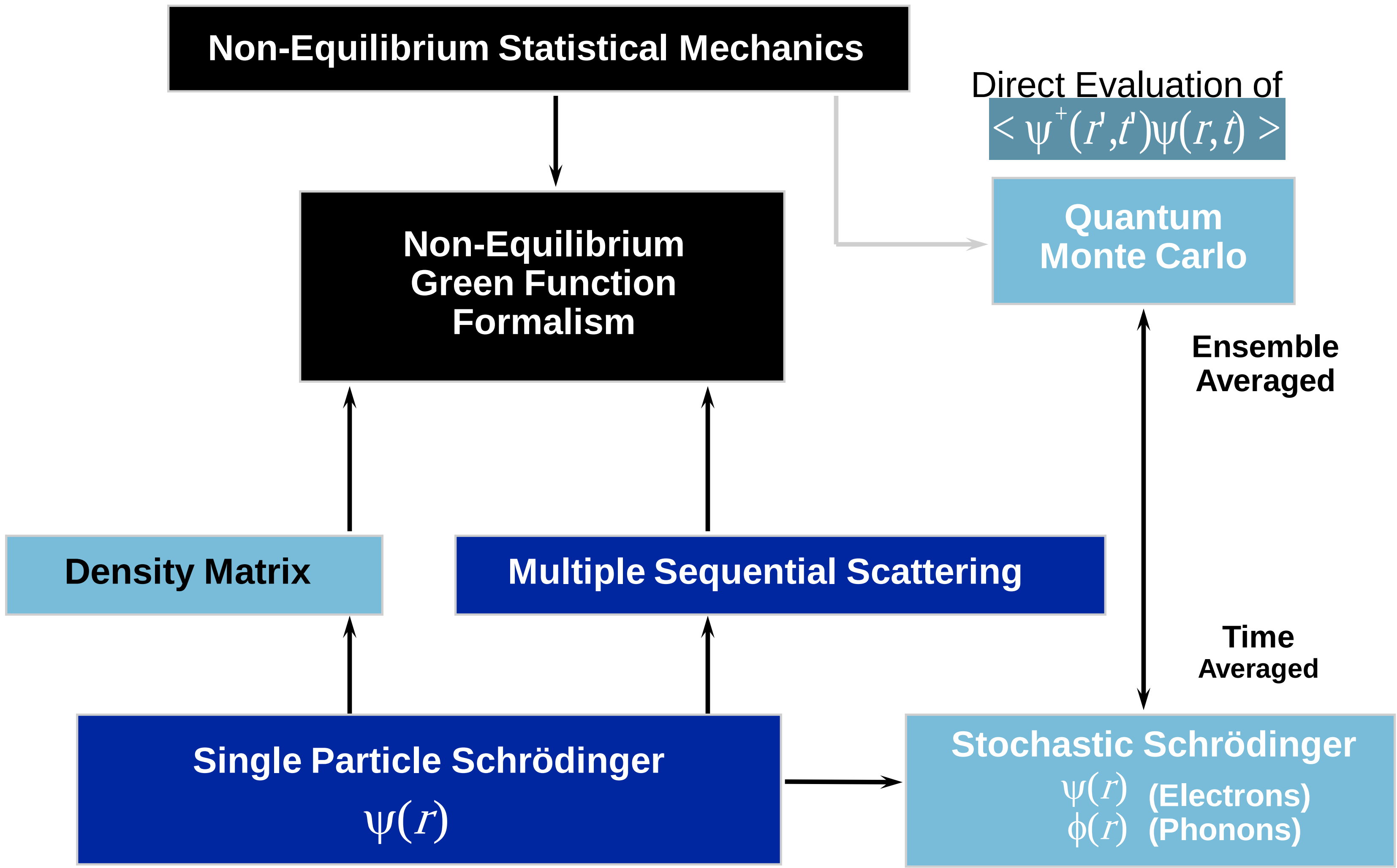
- 1-D Poisson Schrödinger
  - » Quantum transmitting boundary conditions (QTBM), flatband (Lent)
  - » Single band, effective mass, no scattering ("everyone")
  - » Multiple Sequential Scattering (Roblin)
  - » Tight binding, no scattering (Boykin, Ting)
- Density Function
  - » Single band, no scattering, time dependent (Ferry)
- Wigner Function
  - » Single band with empirical scattering (Frensley)
- NEGF
  - » Single band with scattering (Lake, Jauho)
  - » Single band with charge self-consistency (Klimeck)
- **SCATTERING is the source of the valley current**

Limitations:

- Tiny device simulation domains – no extended contact regions
- No realistic scattering models
- Computation too expensive for engineering (we can build this in one month)
- No predictive theory, modeling, and simulation

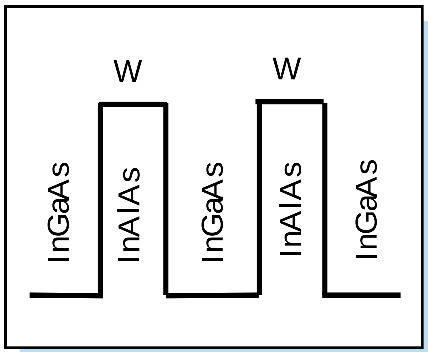
Available and Explored Theories

- The non-equilibrium Green function formalism underlies NEMO.
- All of the approaches shown were considered.
- Approaches in light blue were dropped. Approaches in dark blue were incorporated.

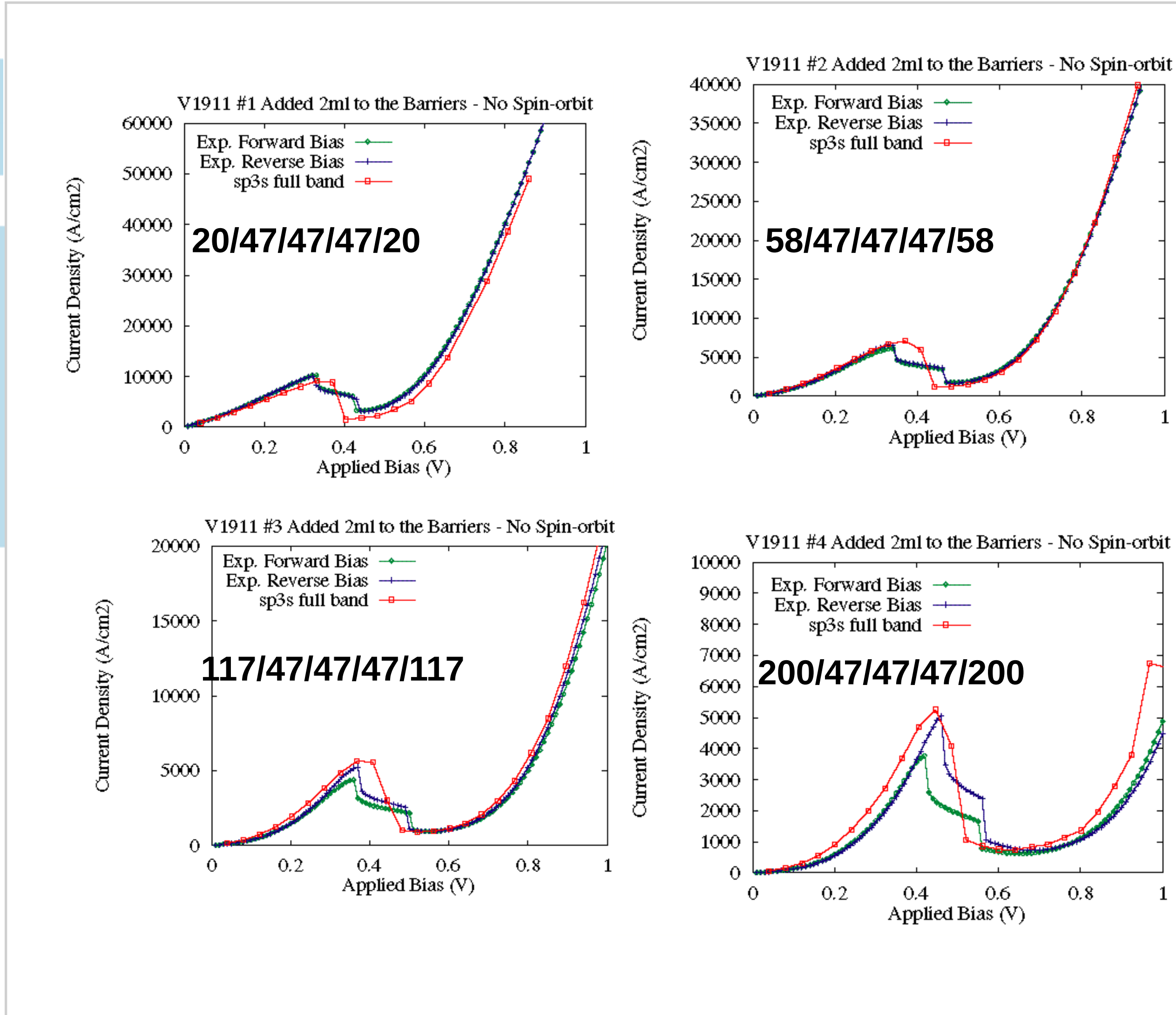


4 Stack RTD with Spacer Variation

Vary Spacer Length

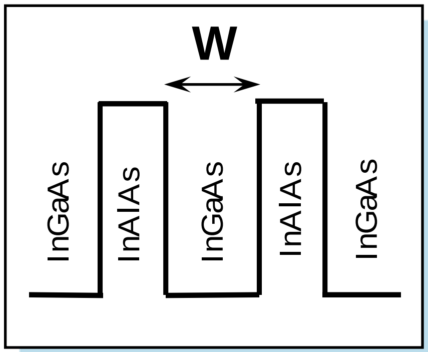


Four nominally symmetric devices:
20/47/47/47/20 A [1]
58/47/47/47/48 A [2]
117/47/47/47/117 [3]
200/47/47/47/200 [4]



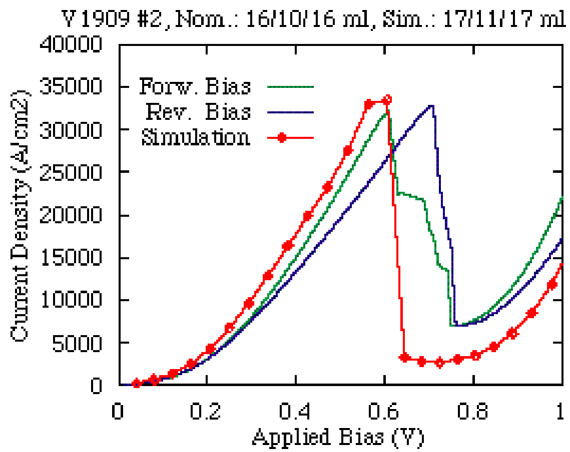
4 Stack RTD with Well Width Variation

Vary Well Width

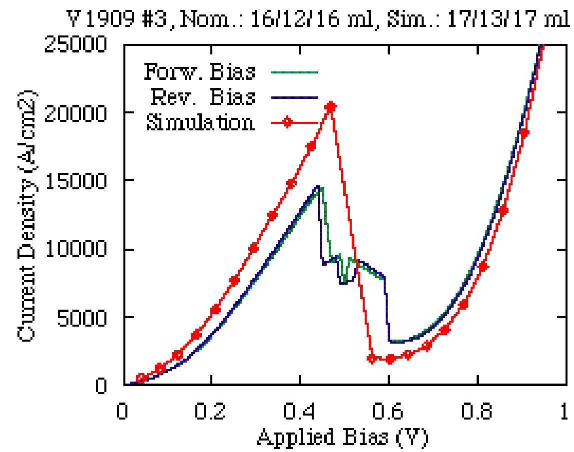


Three nominally symmetric devices:
47/29/47 A [1]
47/35/47 A [2]
47/47/47 A [3]

One asymmetric device:
35/47/47 A



20/47/29/47/20



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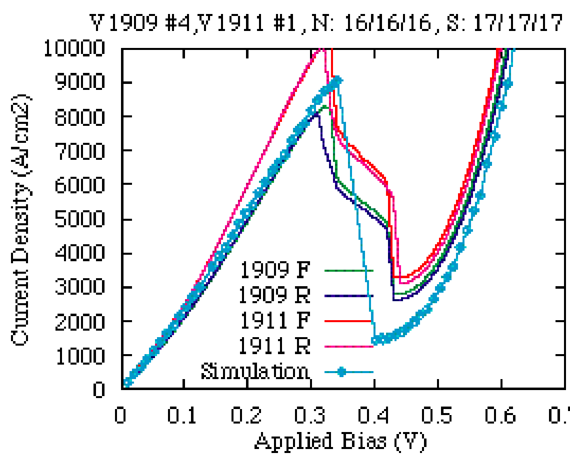
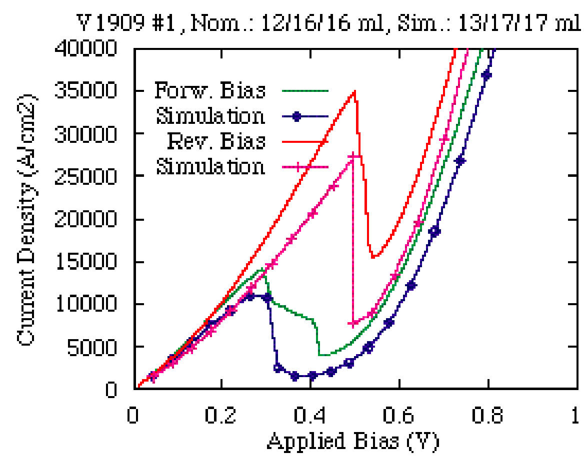


20/47/47/47/20

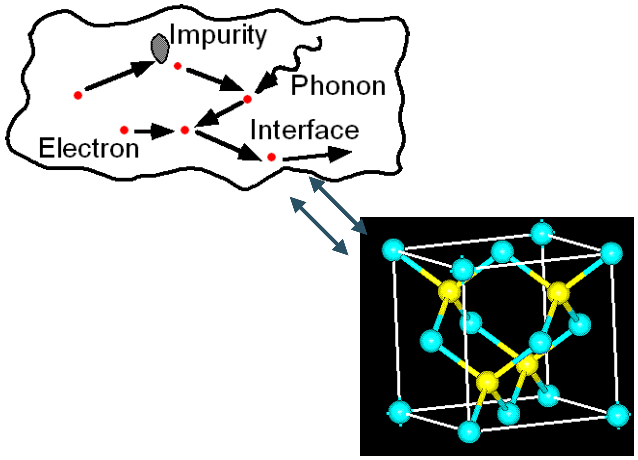


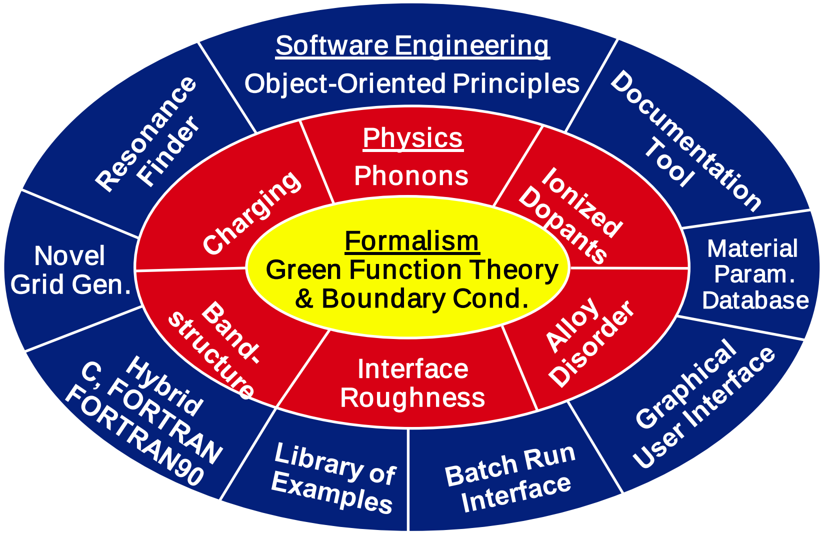
20/35/47/47/20

NEMO: A User-friendly Quantum Device Design Tool

- **NEMO 1-D was developed under a NSA/NRO contract to Texas Instruments and Raytheon from '93-'98 (>50,000 person hours, 250,000 lines of code).**
- **NEMO 1-D maintained and NEMO 3-D developed at JPL '98-'03 (>14000 person hours) under NASA, NSA, and ONR funding.**

- **NEMO is THE state-of-the-art quantum device design tool.**
  - » **First target: transport through resonant tunneling diodes (high speed electronics).**
  - » **Second target: electronic structure in realistically large nano devices (detectors).**
  - » **Third target: qbit device simulation.**
  - » **Ultimate target: Educational tool - heterostructures, bandstructure, transport.**
- **Bridges the gap between device engineering and quantum physics.**
- **Based on Non-Equilibrium Green function formalism NEGF - Datta, Lake, Klimeck.**
- **Currently used by limited number of government labs and few Universities.**





State-of-the-art RTD Modeling and Simulation Knowledge 1998

Knowledge:

- Scattering inside RTD
  - » Only important at low temperatures
  - » Not important for room temperature, high performance
- Scattering inside extended contacts
  - » Of critical importance at any temperature
- Charge self-consistency
  - » Critical everywhere, contacts and central device
- Bandstructure – atomistic device resolution
  - » Critical for understanding high temperature, high performance devices
- NEGF is the baseline of an industrial strength simulator

Availability:

- An engineering modeling and design tool for 1D heterostructures
- Experimentally verified – **analysis and design**

Releasing NEMO1-D has been a Struggle

Even a movie was made!

Currently only available through JPL for government use!

We need public-domain codes as field develops!

NEMO 3-D can be found for free at: https://nanohub.org/groups/nemo_3d_distribution

The other Nemo has also been found: