1) Introduction to Quantum Confinement and Resonant Tunnelling Diodes

Quantum confinement occurs when a particle such as an electron is confined on the length scale of its wavelength. When an electron is strongly quantum confined, it can only exist at discrete energy levels.

Resonant Tunnelling Diodes (RTDs):
- One of the simplest quantum confinement structures
- Consists of a matrix of atoms (left), defining a quantum well (right)
- Central region is sufficiently small to form discrete energy levels ($E_1$)
- Energy level is very sensitive to the atomic constituents of the well

2) RTDs as Physically Unclonable Functions

Physically Unclonable Functions (PUFs):
- Unique physical objects that cannot be recreated
- Translates an applied challenge to a unique response
- Can act as ‘fingerprint’ for attached circuitry or objects

Genuine PUF Challenge: PUF A \[\text{A: 01101110}\]
Counterfeit PUF Challenge: PUF A* \[\text{A: 01100101}\]

If voltage is controlled over RTD, we have a PUF:
- At voltage of peak ($V_p$), the most electrons have energy $E_1$
  - $V_p$ position directly depends on energy level position $E_1$
  - $E_1$ depends on precise atomic arrangement in the well
- Replication requires characterising and fabricating the device at atomic-level resolution (impossible)

3) RTDs for Quantum Random Numbers

Quantum Random Number Generators (QRNGs):
- Unpredictable random number generator
- Uses quantum processes that are entirely indeterminable
- Cannot predict output, even with knowing entire system

If current is controlled over the RTD, we have a QRNG:
- At peak current ($I_p$), incident electron can pass 1 of 2 ways:
  - 50% chance of tunnelling through the barriers
  - 50% chance of jumping over the barriers
- The path the electron takes is quantum non-deterministic, and so cannot be predicted, but can be easily measured

4) RTDs in CMOS

Typical resonant tunnelling diodes use III/V semiconductor material (Left – InGaAs/AlAs)
This material can’t be directly integrated into CMOS circuit fabrication processes
Work is being done to produce RTDs in CMOS-compatible silicon (Right – Si/SiO$_2$)