MODELLING SPACE-CHARGE-LIMITED CURRENT (SCLC) IN SEMICONDUCTORS

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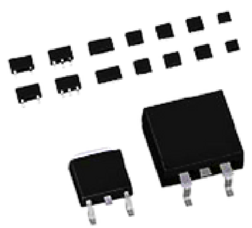
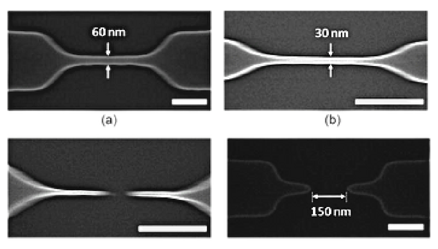
01 BACKGROUND INFORMATION

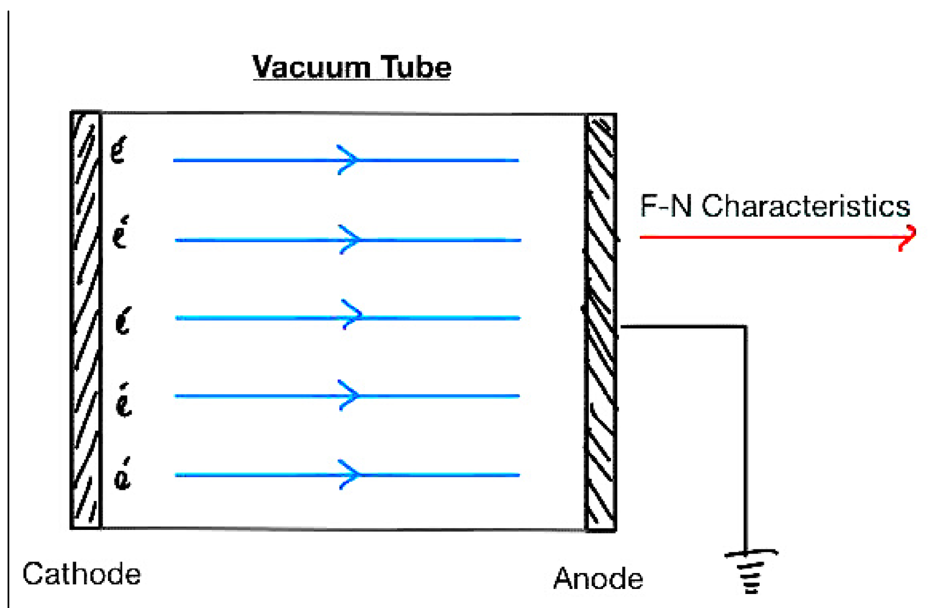
Vacuum Tubes - 1950s
- Used in first-generation computers, radios, transmitters
- Cons: Large in size, fragile, high energy usage

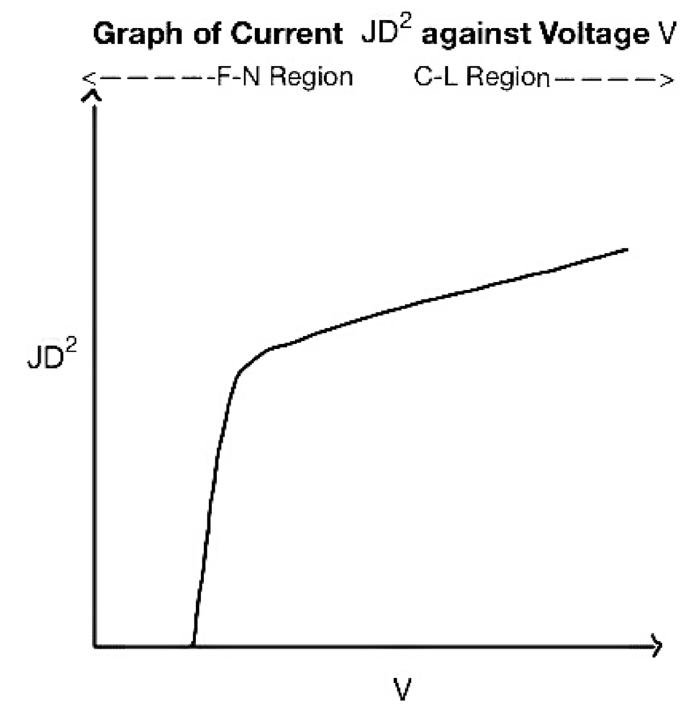


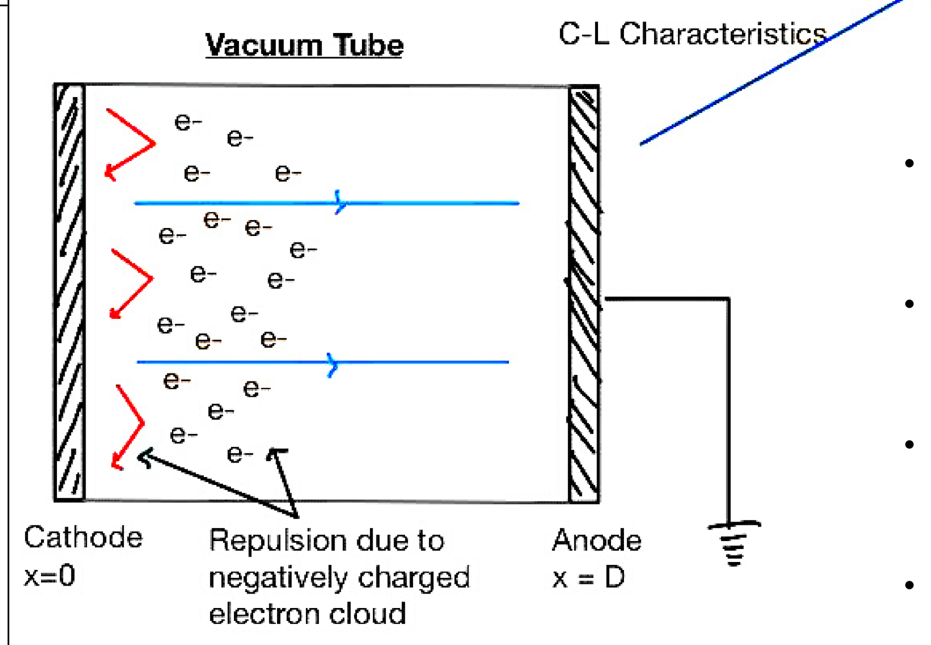
Solid State Transistors
- Semiconductor device
- Pros: Much smaller, reduced energy usage
- Cons: Vulnerable to EMP blat (strong E field) - fry semiconductor chip



Modern Vacuum nano-electronics
- Remains relevant in key electronic systems:
  - Radar Systems, Electronic Warfare, Spacecraft, Microwave communication systems



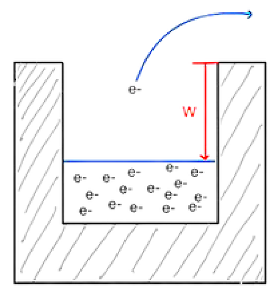




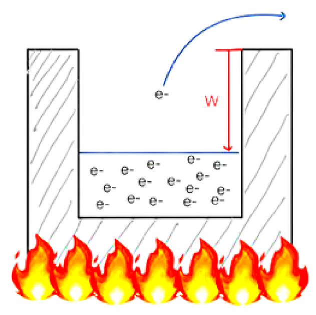
Types of Electron Emission
- Liberation of electrons from the surface that is stimulated by radiation (lasers), temperature (heating element), strong electric field (quantum tunnelling)

Photoelectric Effect
- Emission due to EM Waves

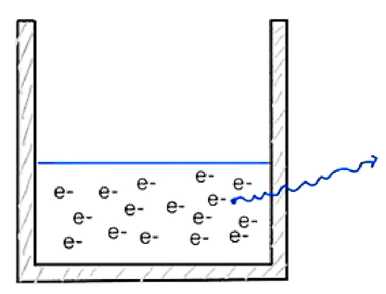
hf>W: electron escapes well
hf<W: electron can't escape and oscillates



Thermionic Emission
- Emission due to thermal eg. from a resistor



Field Emission
- Reduces the barrier of the well which allows for quantum tunnelling



- A **Vacuum Tube** consists of an Anode and Cathode, separated by a vacuum. It controls electric current flow (e-)
- Usually, when an electron is emitted it is repelled by the cathode(-ve) and is accelerated by the anode (+ve)
- However, at **high voltages**, the emitted electrons **saturate** the vacuum space which repels low-energy electrons
- This results in a **Space Charge Limited Current**

02 PROBLEM STATEMENT

How does current conduction transit from field emission to space charge limited in semiconductors?

03 MODELLING SCLC WITHOUT COLLISION

Using the Fowler-Nordheim Law, Poisson's Equation and conservation of energy, the equation for the velocity and displacement of an electron (vacuum field emission) can be derived

Vacuum

Conservation of energy: $eV = \frac{1}{2}mv^2$

Poisson equation: $\frac{d^2V}{dx^2} = \frac{en}{\varepsilon_0}$

Poisson equation (Llewllyn form): $\frac{d^2v}{dt^2} = \frac{eJ}{m\epsilon_0}$.

Traditional Fowler-Nordheim Law: $J = AE_S^2 e^{-\frac{B}{E_S}}$

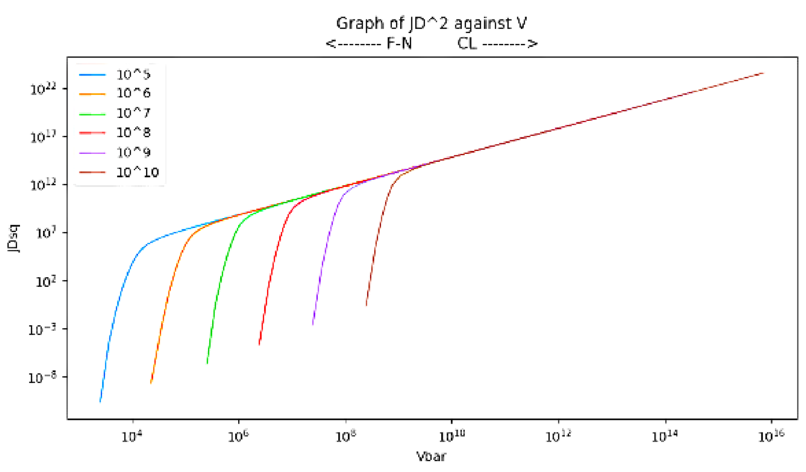
$$x(t) = \frac{eJ}{6m\epsilon_0}t^3 + \frac{eE_S}{2m}t^2$$
$$v(t) = \frac{eJ}{2m\epsilon_0}t^2 + \frac{e}{m}E_S t$$

As the direct J-V relationship is difficult to derive analytically, E is used as an intermediary variable to determine their relationship numerically

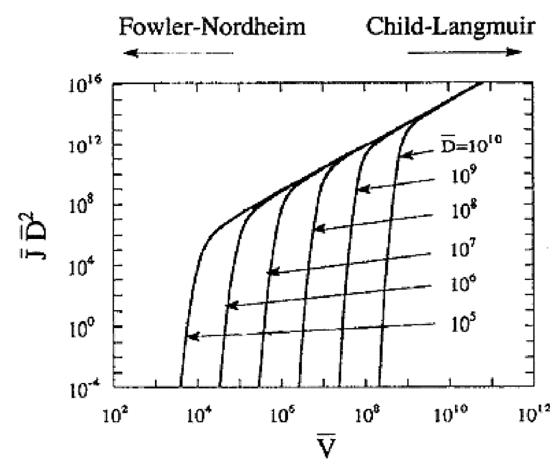
$$\xi^2(\xi+3) = 6\bar{D}\bar{E}(e^{-2/\bar{E}})$$

$$\xi = -1 + \sqrt{1 + 2(2\bar{V})^{0.5}e^{-1/\bar{E}}}$$

$$\bar{T} = \frac{\xi}{\bar{E}}e^{1/\bar{E}}$$



Graph generated in python



Graph in 1994 paper

Using these equations, a J-V graph was generated to verify the transition from Fowler-Nordheim Law (Field Emission) to Child-Langmuir Law (Space Charge Limited Current) against the 1994 paper (Lau, Liu and Parker, 1994).

04 MODELLING SCLC WITH COLLISION

Having modelled the transition from field emission to space charge limited current in a vacuum, a model taking into account electron mobility (in solid-state materials for instance), as well as non-typical emission surfaces, can be constructed.

Solid State Materials

$$\sum F = ma \qquad eE - \frac{e}{\mu}V = ma$$

Generalised Fowler-Nordheim Law:

$$J = AE_S^{\beta}e^{-\frac{B}{E_S}}$$

$$\bar{J} = \frac{d^2\bar{v}}{d\bar{t}^2} + \frac{1}{\bar{\mu}}\frac{d\bar{v}}{d\bar{t}}$$

Non Dimensionless Units

$$\phi = \phi_0\bar{\phi}; \quad J = J_0\bar{J}; \quad x = x_0\bar{x}; \quad t = t_0\bar{t};$$
$$\mu = \mu_0\bar{\mu}; \quad E = E_0\bar{E}; \quad v = v_0\bar{v}$$
$$\phi_0 = \frac{e\epsilon_0^2}{mA^2}; \quad J_0 = AB^2; \quad x_0 = \frac{e\epsilon_0^2}{mA^2B}; \quad t_0 = \frac{\epsilon_0}{AB};$$
$$\mu_0 = \frac{e\epsilon_0}{mAB}; \quad E_0 = B; \quad v_0 \equiv \frac{x_0}{t_0},$$

$$\bar{v}(\bar{t}) = \bar{\mu}\left[(\bar{\mu}\bar{J} - \bar{E})\left(e^{-\bar{t}/\bar{\mu}} - 1\right) + \bar{J}\bar{t}\right]$$

$$\bar{x}(\bar{t}) = \bar{\mu}\left[(\bar{\mu}\bar{J} - \bar{E})\left(-\bar{\mu}e^{-\bar{t}/\bar{\mu}} - \bar{t} + \bar{\mu}\right) + \bar{J}\bar{t}^2/2\right].$$

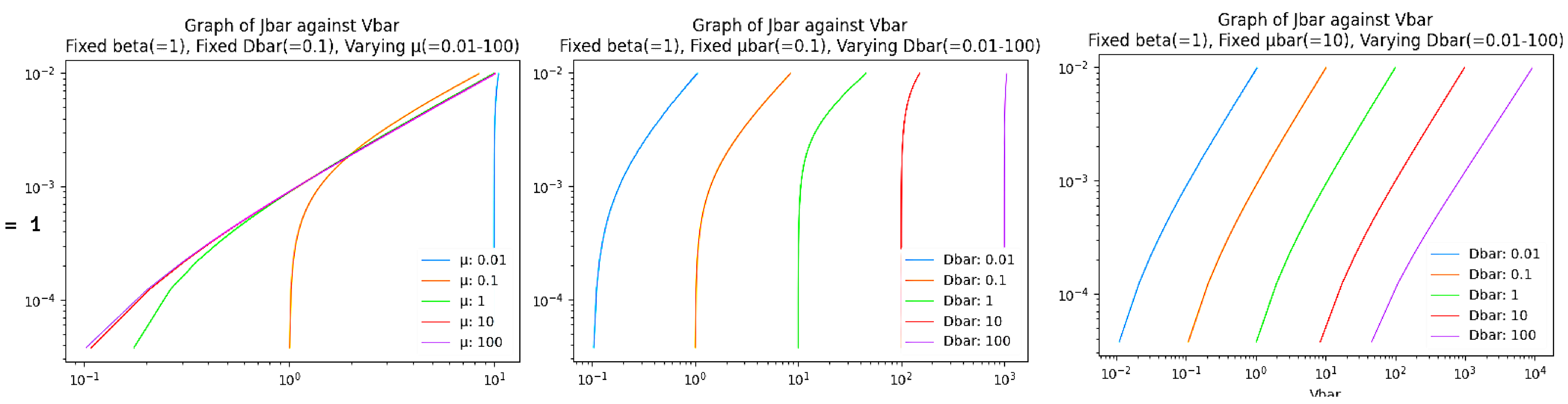
$$\bar{V} = \frac{\bar{v}(\bar{t})^2}{2}\Big|_0^{\bar{T}} + \int_0^{\bar{T}} d\bar{t}\,\frac{\bar{v}(\bar{t})^2}{\bar{\mu}} \qquad \bar{J} = \bar{E}^2 e^{-1/\bar{E}}$$

Numerical Method to Model J against V with varying μ and D:

1. Define a fixed D.
2. Simulate x(t) at a variable E. Keep increasing the time step until x(t) = D. Transit Time (t_tr) is the time taken for the electron to travel length D.
3. Find terminal velocity v(t_tr).
4. The voltage, V can then be calculated from t_tr and v(t_tr)
5. Calculate J based on the E chosen in Step 2.
6. Record J(E) and V(E)
7. Repeat 2 to 6 for different E
8. Plot J(E) versus V(E) in a log-log plot
9. Repeat 1 to 8 for different D.
10. Repeat 1 to 9 for different μ.
11. Repeat 1 to 10 for different β

05 RESULTS

Beta = 1



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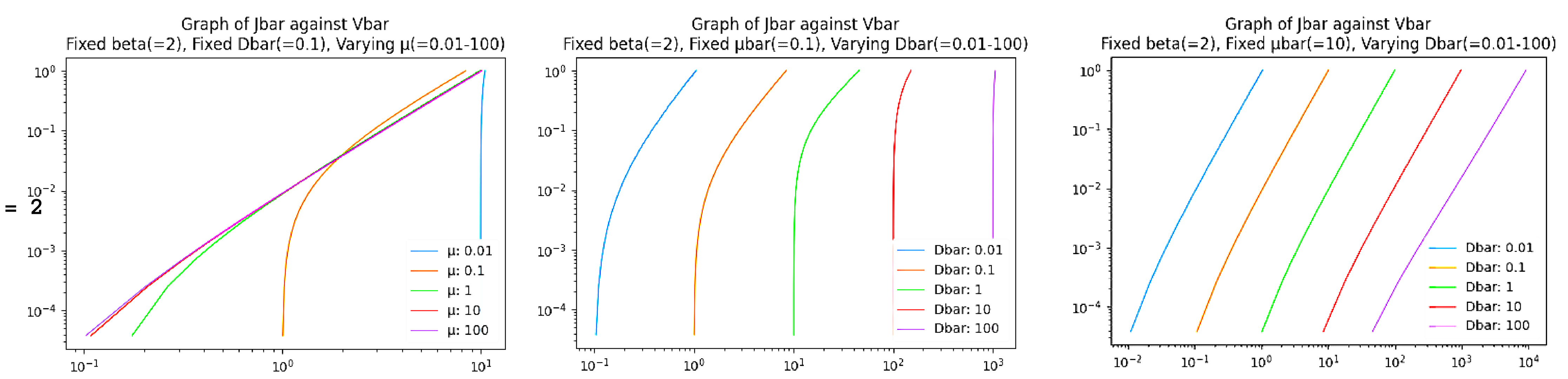

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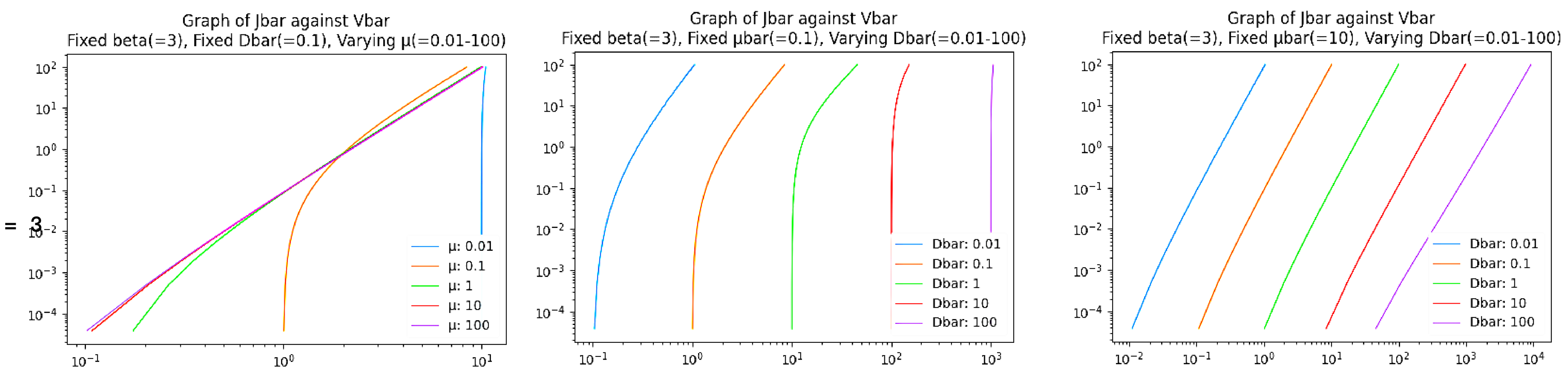

06 CONCLUSION & FUTURE PLANS

- The modelled transition from field emission to space-charge limited current using FN and Poisson equations at different μ and β
- The result modelled for **lower β** is more relevant to **low-current** applications such as EMP-resilient electronics
- The result modelled for **higher β** is more relevant to **high-current** applications such as industrial defence applications
- Models can be plotted onto multidimensional graphs to visualise all variables
- Develop a similar model for thermionic emission.

RELATED LITERATURE

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