Effects of a Series Resistor on Quantum Tunneling Current in Dissimilar Metal-Insulator-Metal Nanogap

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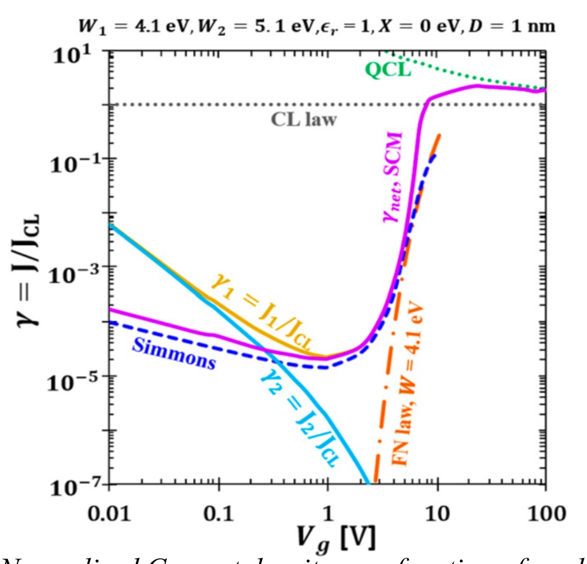
I. Introduction

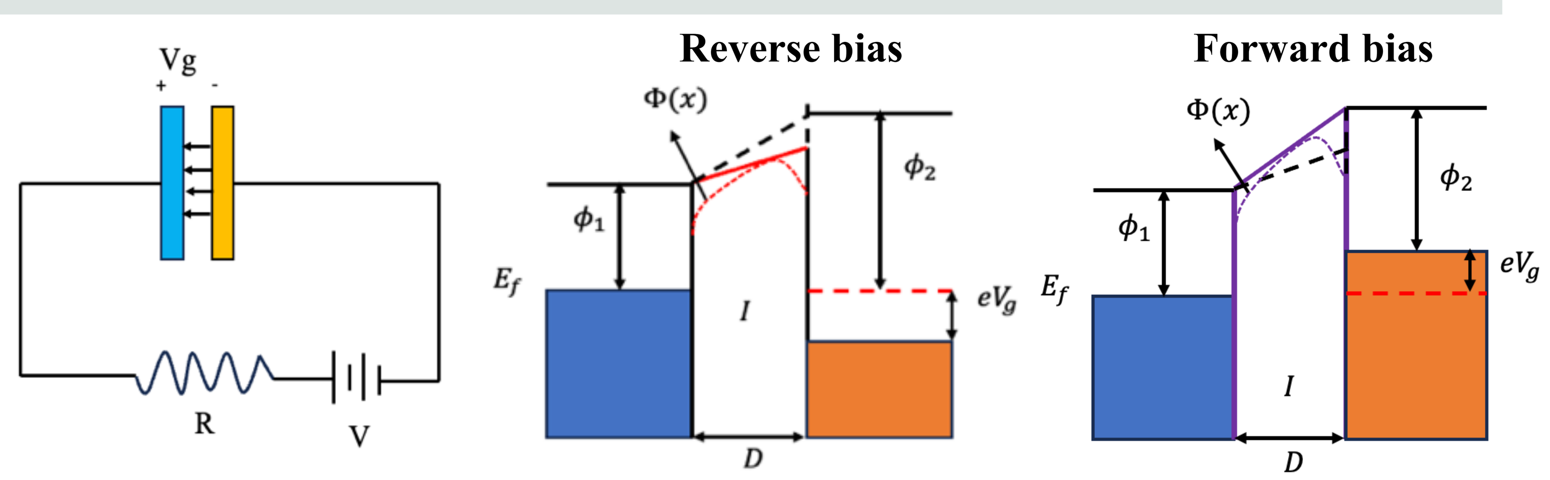
- Quantum tunneling effect plays a crucial role in the development of tunneling field-effect transistors (TFETs) and novel vacuum nano-devices. The necessary interconnects of the circuits inevitably introduce a parasitic series resistance to the nanodevice.
- It is essential to precisely characterize the **current-voltage behaviors in nanoscale metal-insulator-metal (MIM) junctions** across a broad range of material properties and dimensional configurations. The current density-voltage relationship could be divided into three regimes(Fig. 1): **direct tunneling**, **field emission**, and **space-charge-limited regime**. It would be useful in memory devices such as dynamic random-access memory (DRAM) capacitors or memristors.
- In this work, we apply the Zhang and Banerjee's model[1], [2] to a dissimilar MIM nanogap with a series resistor. We provide a detailed study on the effects of **series resistor** on current voltage characteristic curves for different voltage regimes, which is either parasitic to nanoscale circuits, or intentionally added to improve the stability[3] of the current and reduce the abrupt rise.



Two electrodes having work function $W_1 = 4.1eV, W_2 = 5.1eV$, insulator layer $\varepsilon_r = 1$, gap distance $D = 1$ nm.

Fig. 1: Normalized Current density as a function of applied voltage[1].

II. Models



- **Self-consistent model**

Schrödinger equation: $$\frac{d^2q}{d\bar{x}^2} + \lambda^2\left[\phi - \frac{\phi_{xc}}{\phi_g} - \frac{4}{9}\frac{(\gamma_1-\gamma_2)^2}{\phi_g} + \overline{E_0}\right]q = 0$$

Poisson's equation: $$\frac{d^2\phi}{d\bar{x}^2} = \frac{2}{3}\frac{q^2}{\varepsilon_r}$$

With the boundary conditions:

$\phi(0) = 0,\ \phi(1) = 1$

$q(1) = \{A[\gamma_1 + \gamma_2 + 2\sqrt{\gamma_1\gamma_2}\cos(B)]\}^{1/2}$

$q(1)' = \frac{4}{3}\left(\frac{\lambda\sqrt{\gamma_1\gamma_2}}{q(1)}\right)\sin(B)$

where $A = \frac{2}{3\sqrt{1+\overline{E_0}}}$, $B = 2\lambda\sqrt{1+\overline{E_0}}$

Electric potential: $\phi = \frac{V(x)}{V_g}$
Dimension: $\bar{x} = \frac{x}{D}$
Exchange-correlation potential $\phi_{xc} = \frac{\Phi_{xc}}{E_H}$
Biased voltage: $\phi_g = \frac{eV_g}{E_H}$
Net current density: $\gamma = \frac{J}{J_{CL}}$
Electron emission energy: $\overline{E_0} = \frac{E_0}{eV_g}$
Electron density: $\bar{n} = \frac{n}{n_0} = \frac{\psi\psi^*}{n_0}$
Wavelength: $\lambda = \frac{D}{\lambda_0}$, where $\lambda_0 = \sqrt{\frac{\hbar^2}{2em_eV_g}}$
Child-Langmuir Law : $J_{CL} = \frac{\frac{4}{9}\epsilon_0\sqrt{\frac{2e}{m_e}}V_g^{\frac{2}{3}}}{D^2}$

The normalized emission current density from two electrodes γ_1 and γ_2 are:

$$\gamma_1 = \frac{9}{4\pi\sqrt{2}}\frac{\lambda^2}{\phi^{5/2}}\bar{T}\int_0^\infty \ln\left(1 + e^{-\frac{\overline{E_x}-\overline{E_F}}{\bar{T}}}\right)D(\overline{E_x})d\overline{E_x}$$

$$\gamma_2 = \frac{9}{4\pi\sqrt{2}}\frac{\lambda^2}{\phi^{5/2}}\bar{T}\int_0^\infty \ln\left(1 + e^{-\frac{\overline{E_x}+\phi_g-\overline{E_F}}{\bar{T}}}\right)D(\overline{E_x})d\overline{E_x}$$

Hartree energy : $E_H = 27.2\ eV$
Electron Penetrate probability: $D(\overline{E_x})$
Temperature: $\bar{T} = \frac{k_BT}{E_H}$
Electron Energy: $\overline{E_x} = E_x/E_H$
Fermin Energy: $\overline{E_F} = E_F/E_H$

- **Lumped circuit**

$V = V_g + IR = V_g + JSR$

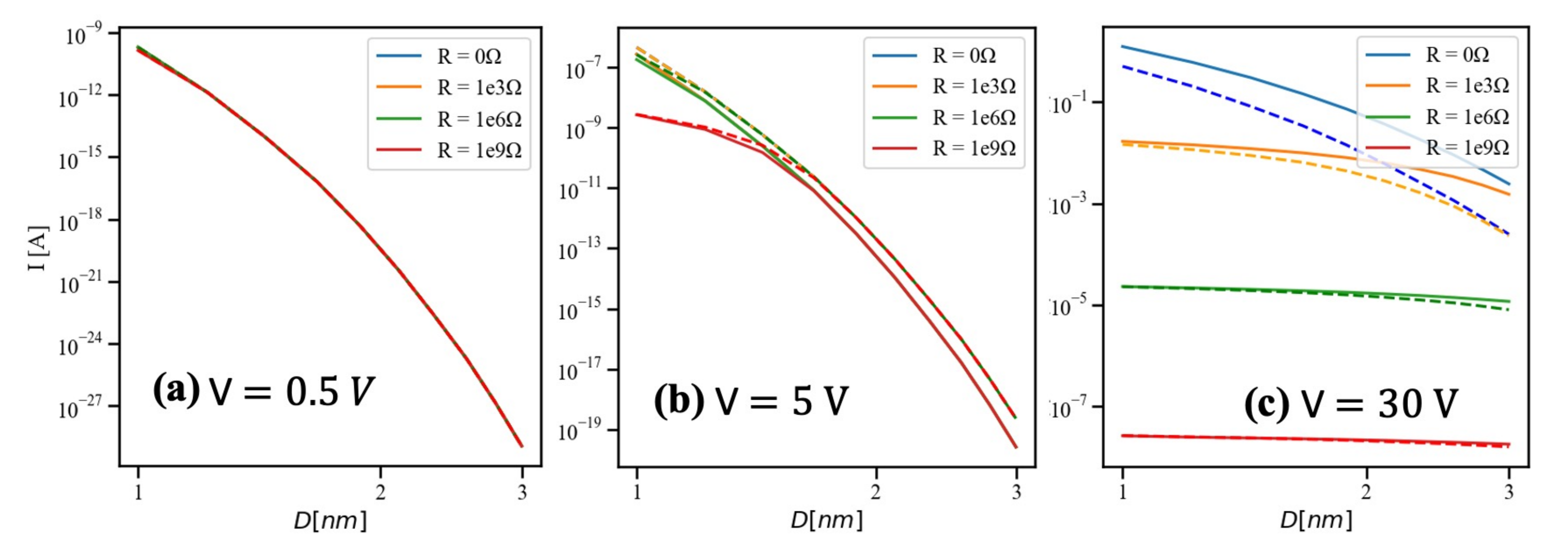
III. Parameters

Work function (Al-Au)	$W_{Al} = 4.08eV, W_{Au} = 5.1eV, \Delta W = 1.02$ eV
Electrode surface area	$S = 70 * 60$ nm^2
Electrode Temperature	$T = 300K$
Electron emission energy	$E_0 = 0$

IV. Results

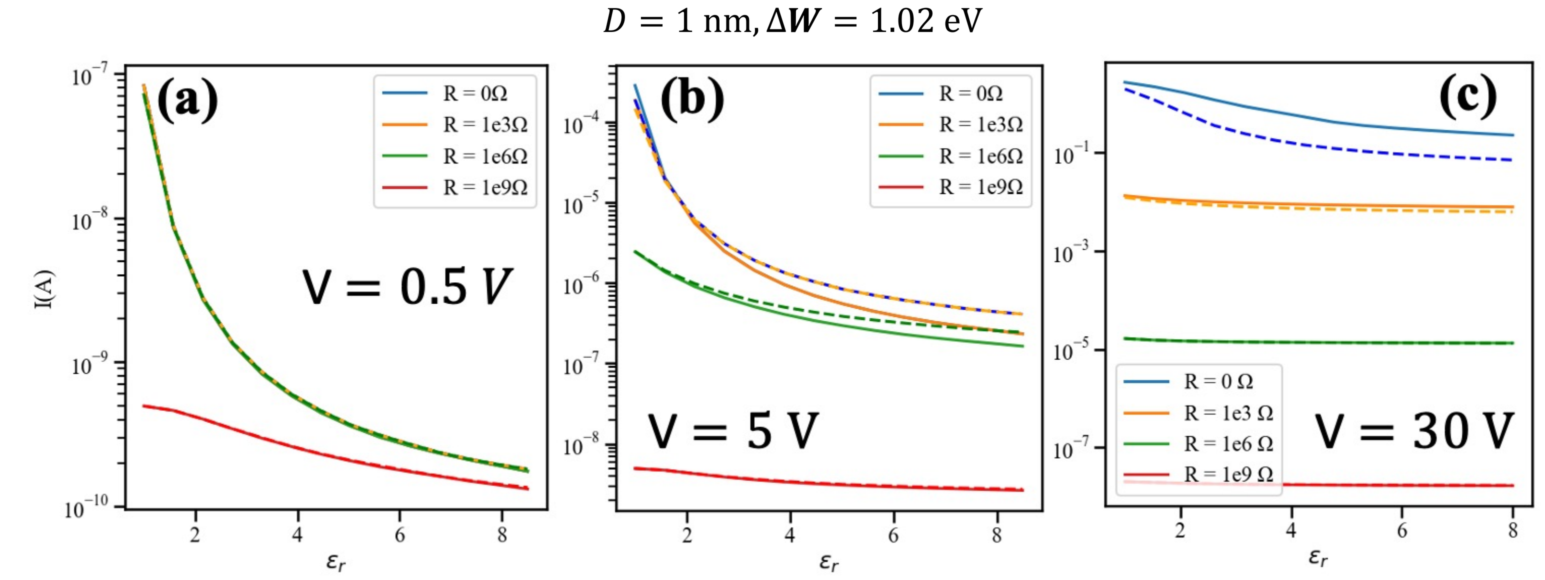
Tunneling Current as a function of **gap distance(D)** for different series resistor of **different voltage regime(V)** under RB(solid line) and FB(dashed line) conditions.

$\varepsilon_r = 7.6, \Delta W = 1.02$ eV



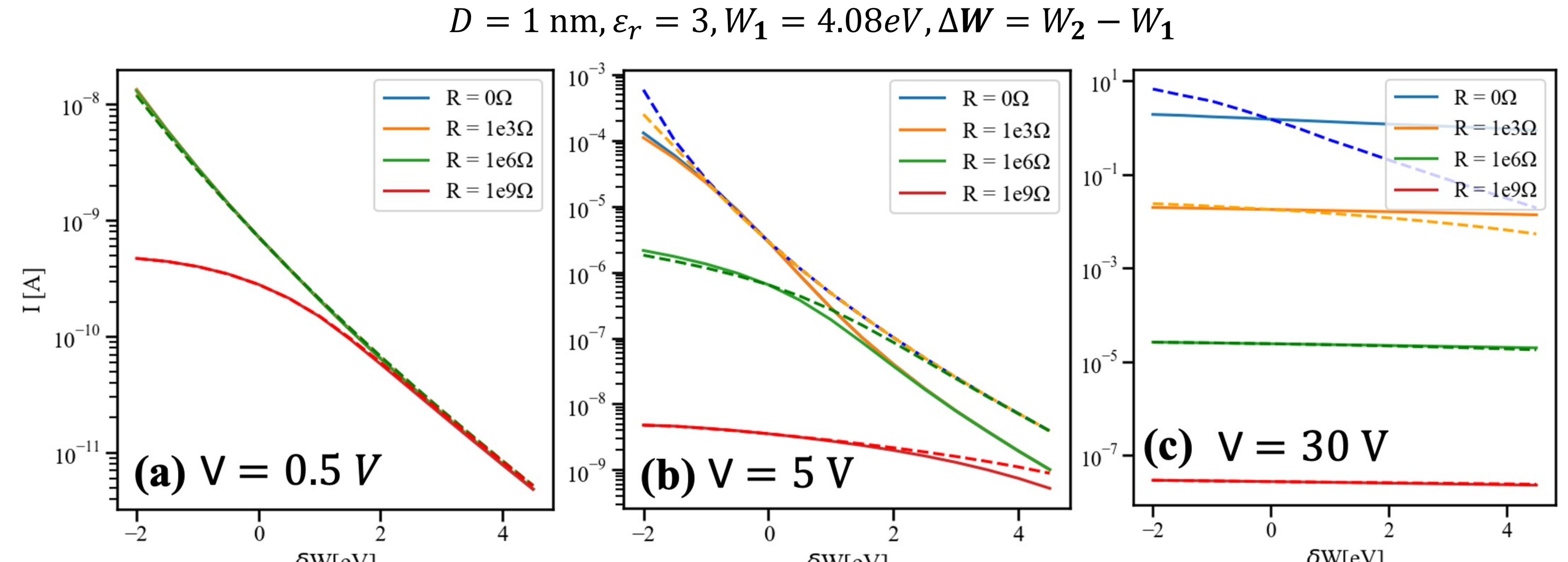
Tunneling Current as a function of **insulating layer permittivity (ε_r)** for different series resistor of **different voltage regime(V)** under RB(solid line) and FB(dashed line) conditions.

$D = 1$ nm$, \Delta W = 1.02$ eV



Tunneling Current as a function of **work function difference(ΔW)** for different series resistor of **different voltage regime(V)** under RB (solid line) and FB (dashed line) conditions.

$D = 1$ nm$, \varepsilon_r = 3, W_1 = 4.08eV, \Delta W = W_2 - W_1$



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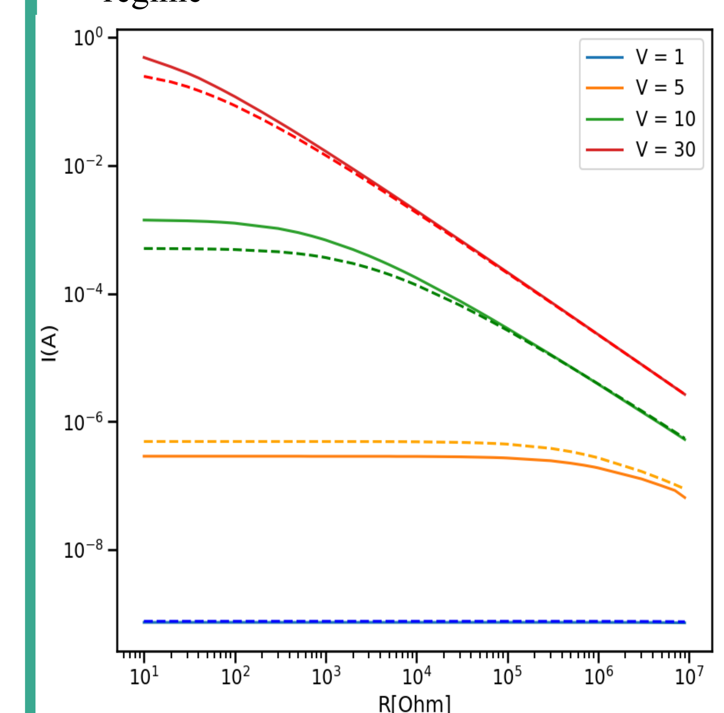
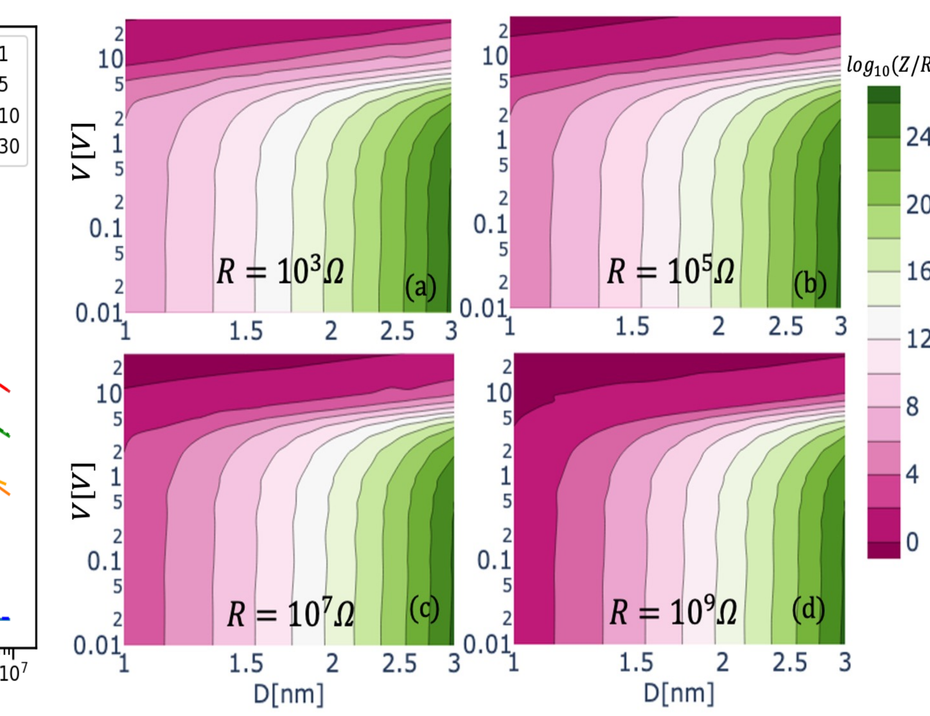
V. Effects of Resistance

The effects of series resistor R on the tunneling current I for different voltage regime



Contour plots - logarithmic scale of impedance (Z) normalized by resistance (R) across varying gap distance(D) and circuit voltages (V)



- At low voltage, the characteristics are almost identical for **FB(solid line) and RB(dashed line).** Resistor ***R*** does not affect the tunneling current- governed by quantum tunneling.
- As resistor ***R*** increases, the difference between FB and RB is not obvious at high voltages, indicating that the impact of the series resistor becomes more dominant than the differences in work function.
- The contour plot clearly marks the boundary where resistor significantly impacts the behavior of dissimilar MIM nano-gap across different voltage and gap distance configurations.
- As ***R*** increases, the impedance is getting larger and approaches the value of R. The impact of ***R*** is more pronounced in regions with small D and high V.

VI. Conclusion

- We investigate the influence of **a series resistor** on the **tunneling current-voltage characteristics** in a **dissimilar MIM nanogap**. The model identifies the regimes where the series resistor is important and provides a quantitative evaluation of its comparative significance.
- Our findings highlight that the influence of ***R*** is most pronounced in regions characterized by small D and high V, where the impedance of the MIM nanogap approaches that of the resistor.

References

[1] S. Banerjee and P. Zhang, AIP Adv., vol. 9, no. 8, p. 085302, Aug. 2019
[2] P. Zhang, Sci. Rep., vol. 5, no. 1, p. 9826, May 2015
[3] J. W. Luginsland, A. Valfells, and Y. Y. Lau, Appl. Phys. Lett., vol. 69, no. 18, pp. 2770–2772, Oct. 1996.