Anisotropic Charge Transport and Current Crowding in Vertical Thin-Film Contacts with 2D Layered Materials

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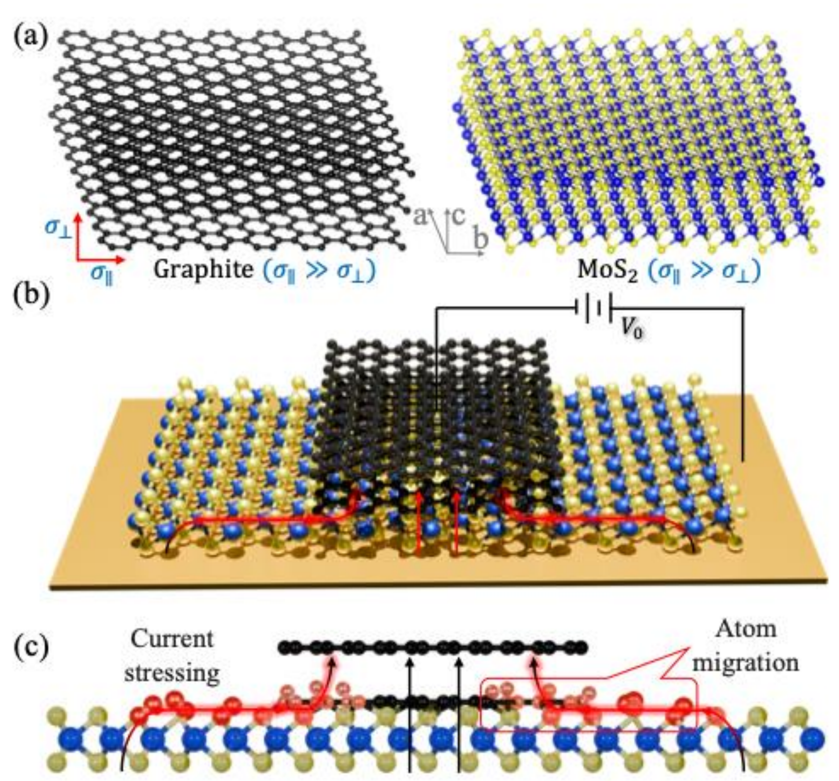
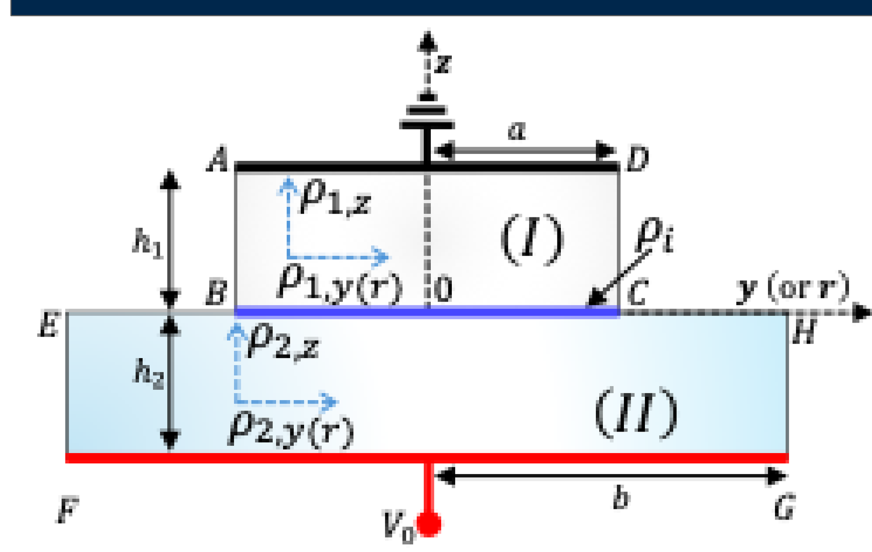
Introduction & Motivation

- ❑ Layered 2D materials (graphene, MoS_2, WSe_2, etc.) exhibit dominant in-plane transport due to high anisotropy.
- ❑ High in-plane conductivity intensifies current crowding at contact edges.
- ❑ Consequences: higher spreading resistance[1], local heating, electromigration, interfacial degradation



Models



Here, $t = y$ for the Cartesian geometry and $t = r$ for the cylindrical geometry and z = axis of rotation for cylindrical. Below R_1 top, R_2 bottom and R_i is the interface resistance. [3]

$R_1 = \rho_{1,z}\, h_1/(2aW)$ (Cartesian)
$R_1 = \rho_{1,z}\, h_1/(\pi a^2)$ (Cylindrical)
$R_2 = \rho_{2,z}\, h_2/(2bW)$ (Cartesian)
$R_2 = \rho_{2,z}\, h_2/(\pi b^2)$ (Cylindrical)

$R_i = \rho_i/2aW$ (Cartesian)
$R_i = \rho_i/\pi a^2$ (Cylindrical)
W width perpendicular to the paper.

Solution of Laplace Equation (∇.(σ∇Φ)=0)

Region I ($0 < z < h_1$) [3]:

$$\Phi_I(y,z) = A_0(z-h_1) + \sum_{n=1}^{\infty} A_n \frac{\sinh\left(\frac{n\pi}{a\sqrt{\alpha_1}}(z-h_1)\right)}{\cosh\left(\frac{n\pi}{a\sqrt{\alpha_1}}h_1\right)} \cos\left(\frac{n\pi}{a}y\right) \quad \text{[1a, Cartesian]}$$

$$\Phi_I(r,z) = A_0(z-h_1) + \sum_{n=1}^{\infty} A_n \sinh\left(\frac{\beta_n}{\sqrt{\alpha_1}}(z-h_1)\right) J_0(\beta_n r) \quad \text{[2a, Cylindrical]}$$

Region II ($-h_2 < z < 0$) [3]:

$$\Phi_{II}(y,z) = V_0 + B_0(z+h_2) + \sum_{n=1}^{\infty} \frac{B_n \sinh\left(\frac{n\pi}{b\sqrt{\alpha_2}}(z+h_1)\right)}{\cosh\left(\frac{n\pi}{b\sqrt{\alpha_2}}h_1\right)} \cos\left(\frac{n\pi}{b}y\right) \quad \text{[1b, Cartesian]}$$

$$\Phi_{II}(r,z) = V_0 + B_0(z+h_2) + \sum_{n=1}^{\infty} B_n \frac{\sinh\left(\frac{\lambda_n}{\sqrt{\alpha_2}}(z+h_2)\right)}{\cosh\left(\frac{\lambda_n}{\sqrt{\alpha_2}}h_2\right)} J_0(\lambda_n r) \quad \text{[2b, Cylindrical]}$$

Boundary conditions: $\rho_i J_z = \Phi_{II} - \Phi_I$ and $J_z = -\frac{1}{\rho_{1,z}}\frac{\partial \Phi_I}{\partial z} = -\frac{1}{\rho_{2,z}}\frac{\partial \Phi_{II}}{\partial z}$, $z = 0$, $|t| \in (0,a)$; $\frac{\partial \Phi_{II}}{\partial z} = 0$, $z = 0$, $|t| \in (a,b)$

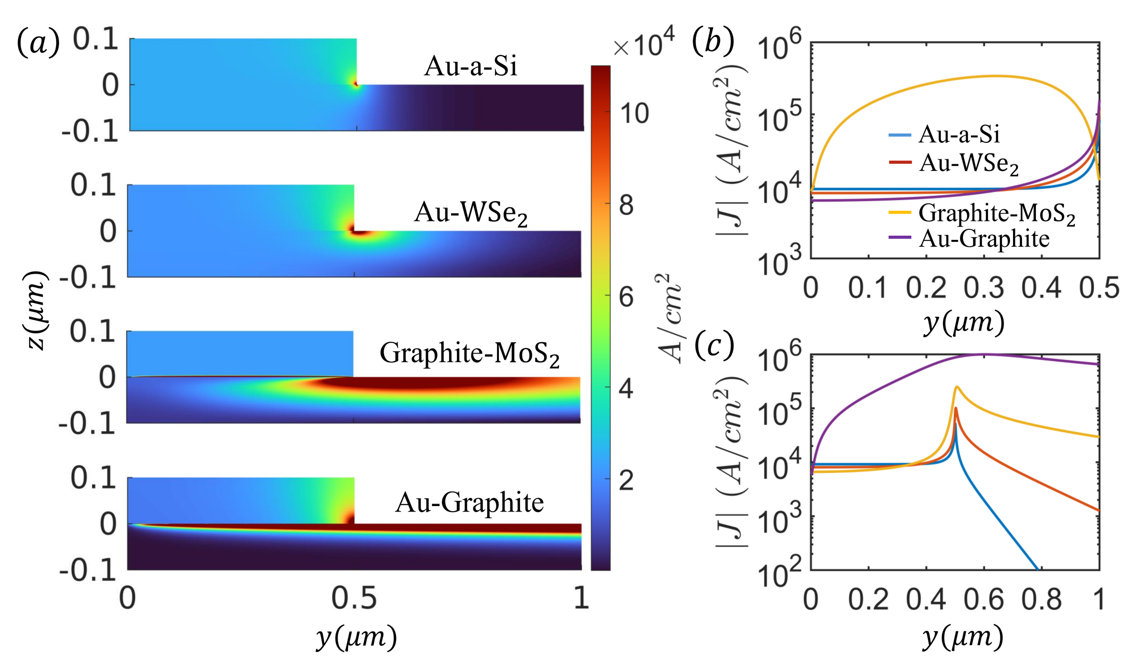
Spreading (Constriction) Resistance, R_S

$$R_S = \frac{\rho_{2,z}}{4\pi W}\overline{R}_s, \text{ and } \overline{R}_s = \overline{R}_s = 2\pi\left\{\frac{\rho_{1,z}}{\rho_{2,z}}\sum_{n=1}^{\infty} B_n \left[\tanh\left(\frac{n\pi}{\sqrt{\alpha_2}}\frac{h_2}{b}\right) + \frac{\rho_i}{\rho_{2,z}b}\frac{n\pi}{\sqrt{\alpha_2}}\right]\frac{\sin\left(n\pi\frac{a}{b}\right)}{n\pi\frac{a}{b}} + \frac{\rho_i}{\rho_{2,z}b}\left(1-\frac{b}{a}\right)\right\} \text{(1c, Cartesian) [3]}$$

$$R_s = \frac{\rho_{2,z}}{4a}\overline{R}_s, \text{ and } \overline{R}_s = \frac{4}{\pi}\left\{2\frac{\rho_{1,z}}{\rho_{2,z}}\sum_{n=1}^{\infty} B_n \left[\tanh\left(\frac{\lambda_n b}{\sqrt{\alpha_2}}\frac{h_2}{b}\right) + \frac{\lambda_n b}{\sqrt{\alpha_2}}\frac{\rho_i}{\rho_{2,z}b}\right]\frac{J_1(\lambda_n a)}{\lambda_n a} + \frac{\rho_i}{\rho_{2,z}b}\left(\frac{a}{b}-\frac{b}{a}\right)\right\} \text{ (2c, Cylindrical) [3]}$$

Where $\alpha_1 = \frac{\rho_{1,t}}{\rho_{1,z}}$ and $\alpha_2 = \frac{\rho_{2,t}}{\rho_{2,z}}$; A_n and B_n are calculated using boundary conditions, current density is $|\boldsymbol{J}| = \sqrt{(\sigma_t\partial_t\Phi)^2 + (\sigma_z\partial_z\Phi)^2}$.

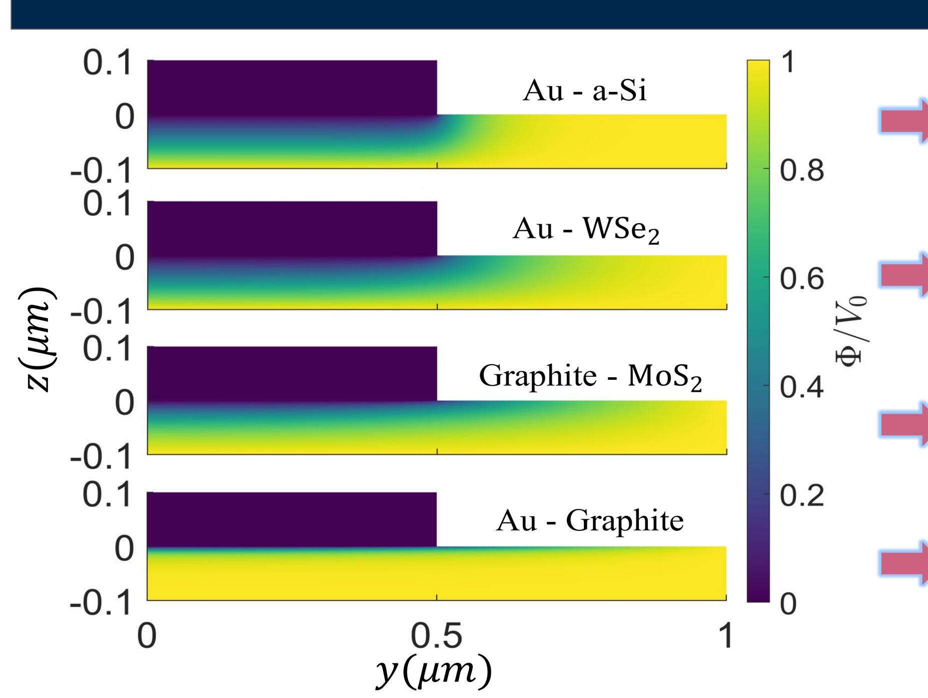
Current Density Distributions



(a) Contour maps of current density $|\boldsymbol{J}|$, (b) Current profiles 5 nm above the interface and (c) Current profiles 5 nm below the interface [3].

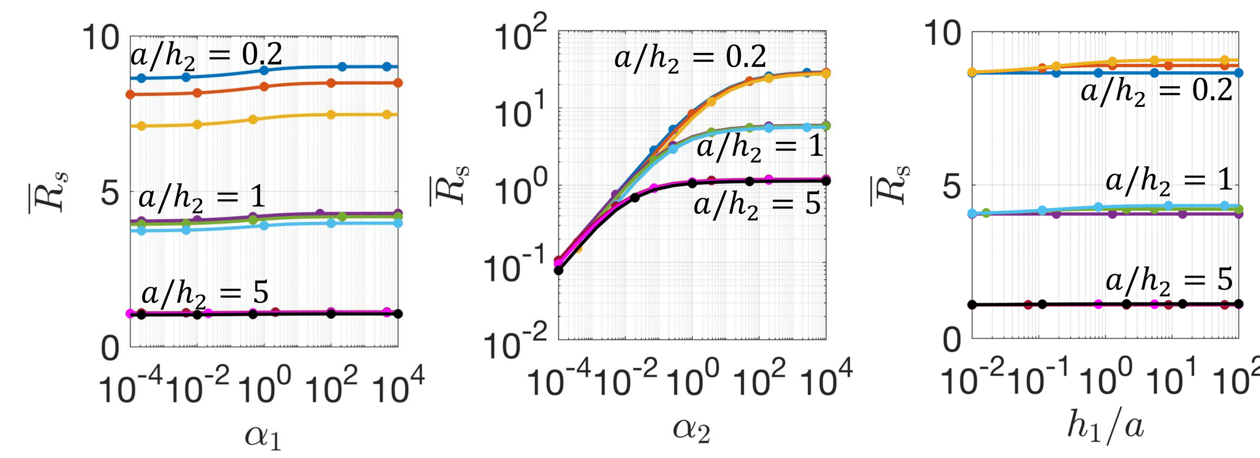
- ➢ **isotropic** (Au - a-Si; $\alpha_1 = \alpha_2 = 1$): nearly uniform spreading.
- ➢ **moderately anisotropic bottom layer** (Au - WSe_2; $\alpha_1 = 1$; $\alpha_2 = 0.1333$): small lateral spreading before injection
- ➢ **both anisotropic layers** (graphite - MoS_2; $\alpha_1 = 2.7 \times 10^{-4}$, $\alpha_2 = 0.009$ **):** amplified lateral flow in both layers
- ➢ **strongly anisotropic bottom** (Au – graphite; $\alpha_1 = 1, \alpha_2 = 2.7 \times 10^{-4}$): extreme in-plane conductivity → delayed vertical injection → extended high-$|\boldsymbol{J}|$ band

Potential Profiles



- uniform vertical penetration, minimal lateral spreading.
- small lateral spreading along in-plane (basal) plane.
- enhanced lateral extension.
- extended lateral potential band, shallow penetration depth.

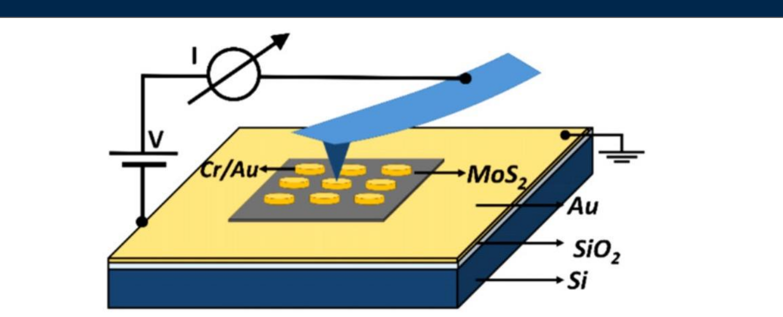
Effect of Anisotropy on R_S



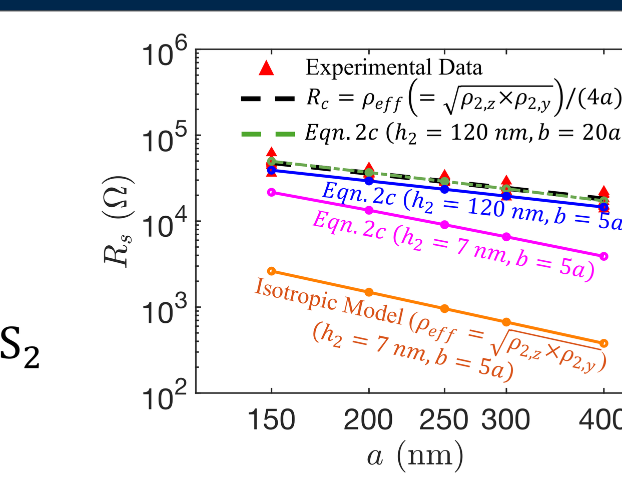
Each a/h_2 set contains three curves for $\alpha_1 = 1000$, 1, 0.001 (top to bottom) with $\alpha_2 = 1$, $b/a = 20$.

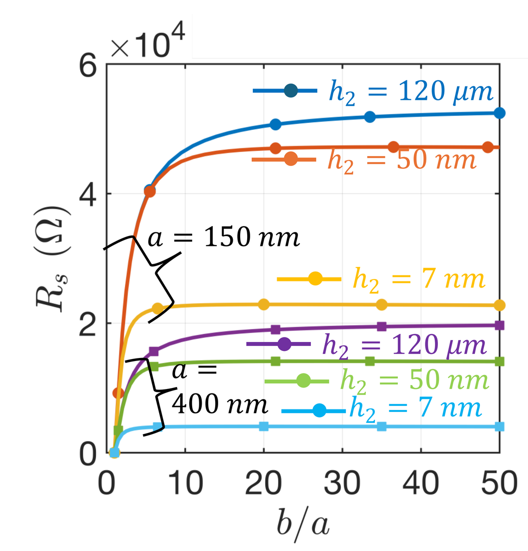
- ❑ $\alpha_1, \alpha_2 < 1$: lower in-plane resistivity → enhanced lateral transport → reduced normalized spreading resistance ($\overline{R}_s$).
- ❑ $\alpha_1, \alpha_2 > 1$: higher in-plane resistivity → stronger constriction → higher ($\overline{R}_s$).
- ❑ $\alpha_{1,2} > 100$: in-plane resistivity has negligible effect.
- ❑ Thicker overlayers ($a/h_2 = 0.2 \rightarrow 5$) give larger $\overline{R}_s$
- ❑ Each a/h_2 set, three curves correspond to b/a = 20, 15, 10 (top to bottom). Larger b/a gives higher $\overline{R}_s$

Experimental Benchmarking of R_S



Conductive-AFM platform for multilayer MoS_2 following Vijayan et al.[2]





Vijayan et al. [2] fitted the measured R_s using the diffusive model, $R_s = \frac{\rho_{eff}}{4a}$, where $\rho_{eff} = \sqrt{\rho_{2,y}\rho_{2,z}}$.

Deviations & limitations: Narrow contacts (b/a < 20) or thin films (few nm) → large departures from 1/a scaling.

Recommendation: Use the full anisotropic field solution, including geometry (a, b, h_1, h_2), interface resistivity (ρ_i), and anisotropy (α_1,α_2). [3]

Acknowledgements

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References

[1] Zhang, P.; Lau, Y. Y. IEEE J. Electron Devices Soc. 1, 83–90 (2013). DOI: 10.1109/JEDS.2013.2261435
[2] Vijayan, G.; Uzhansky, M.; Koren, E. Appl. Phys. Lett. 124, 133101 (2024)
[3] Faisal, M. A.; Zhang, P. Impact of Anisotropic Conductivity on Current Crowding and Spreading Resistance in Vertical Contacts to 2D Thin Films. ACS Applied Electronic Materials 2026, 8, 854-864. (updated this reference after the symposium)