SUPPLEMENTARY INFORMATION

Tuning the ballistic electron transport of spatial graphene-metal sandwich electrode on a vacuum-silicon based device

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1. Child-Langmuir's space-charge-limited current formula

When the emission current increase, charges is continually built up, limiting the surface electric field [see refs 30 in main text]. The space charge effects become important, and I-V characteristics turn into the Child- Langmuir law, given as follows [1-2]

$$J = \frac{4}{9}\varepsilon\sqrt{\frac{2e}{m^*}}\frac{V^{\frac{3}{2}}}{d^2}$$

where ε is the permittivity of medium, m^* is the effective mass of electron, d is distance between cathode and anode, and V is the applied voltage.

2. The Fowler-Nordheim (FN) plot for G-MOS device

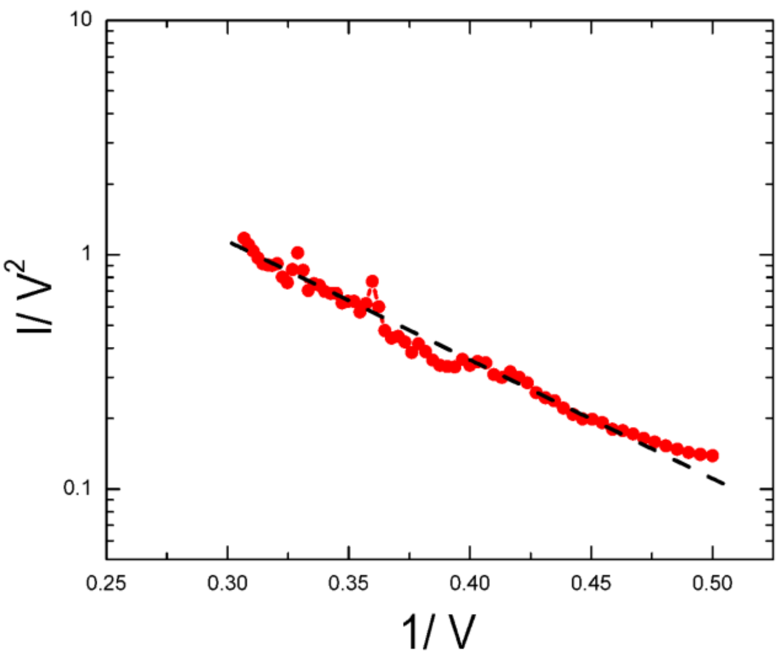
At ~2 V or above, the steeply rising FN current becomes dominant over the SCL component, indicating the near perfect space charge neutralization. The Fowler–Nordheim theory is commonly utilized for electron emission from a metal under a strong applied field. The relationship of total current, I and surface field, F is give as [4]

$$I \sim \left(\frac{F^2}{\phi}\right)\exp(\frac{B\phi^{\frac{3}{2}}}{F})$$

where ϕ is the work function, B =6.83×10^9 [V eV$^{-3/2}$ m^{-1}] . and

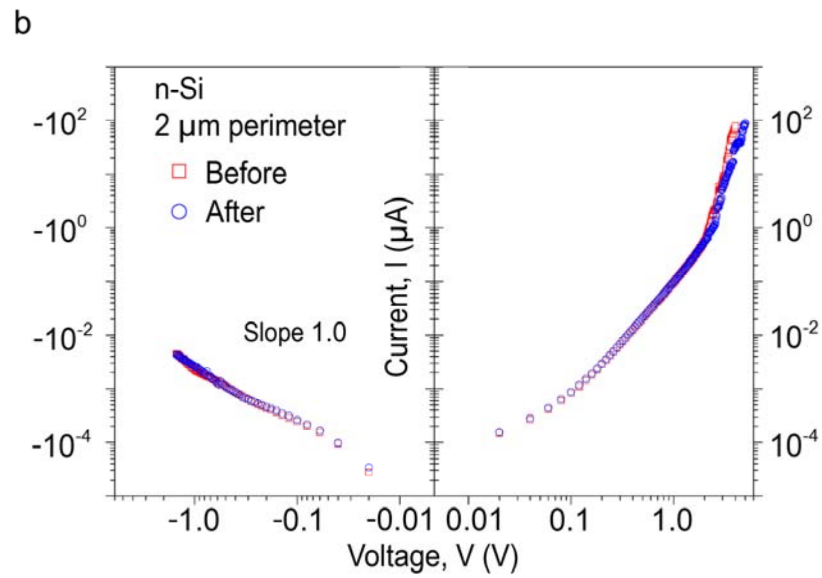
$$F=\beta E=\beta V/d,$$

where V is the applied potential, d is the cathode to anode distance, β the field amplification factor, and $E = V/d$ the local field. The Fowler–Nordheim (F–N) is commonly plotted as ln (I/V^2) versus *1/V, giving* straight line with a slope that depends on above-mentioned factor.



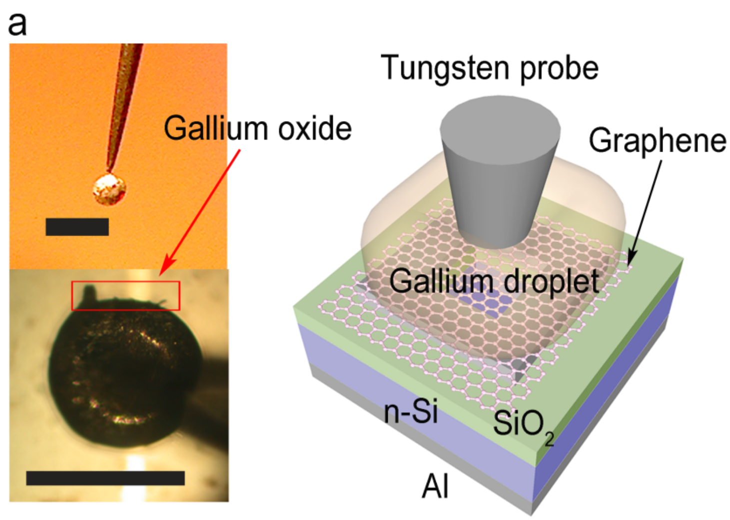
Supplementary Fig 1. Measured I-V characteristics of graphene-Al/SiO2 (23 nm)/n-Si with vertical nano-void channel (500×500 nm area, 2 um depth). The forward I-V characteristic reveal a Fowler-Nordheim (FN) emission current regimes at higher voltage (V ~2V).

3. I-V characteristics of Graphene-MOS, before and after single I-V scan of gallium droplet application.



Supplementary Fig 2. Measured I-V characteristics of Graphene-MOS, before and after single I-V scan of gallium droplet application.

4. gallium oxide forming at the fringe of gallium droplet



Supplementary Fig 3. Gallium oxide forming at the fringe of gallium droplet

5. Charge density calculation of G-MOS and M-G-MOS structure

In general, The work function of intrinsic (undoped) graphene is ~4.56 eV [S2,S3]. The Fermi level of graphene (work function), however, varies depending on the carrier (electron or hole) concentration, n_s, and the Fermi level shift (referring to the Dirac point) can be characterized as [7]

$$\Delta E_F = \hbar |v_F| \sqrt{\pi n_s} \tag{1}$$

Where v_F is the Fermi velocity, 1.1×10^8 cm/s.

Unlike Greaphene-oxide-Si (GOS) structure, both energy band structure of both G-MOS and M-G-MOS is merely determinedt typical MOS capacitor structure. Therefore, the 2dimensional electron density in the semiconductor can be calculated by solving the Poisson equation, expressed as [1]

$$\frac{d^2\varphi}{dx^2} = -\frac{\rho(x)}{\varepsilon}$$

Thus, the space charge density of G-MOS, M-G-MOS and MOS, including GOS structure is expressed as

$$|Q_s| = \varepsilon_s E_s = \frac{\sqrt{2}\varepsilon_s}{\beta L_D}\left[(e^{-\beta\varphi_s} + \beta\varphi_s - 1) + \frac{n_{po}}{p_{po}}(e^{\beta\varphi_s} - \beta\varphi_s - 1)\right]^{1/2} \tag{2}$$

where ε_s is the permittivity of semiconductor, and Es is the electric field at the interface with the oxide layer. φs is the band bending at the semiconductor/oxide interface, called the surface potential. $\beta = q/kT$, and L_D is the extrinsic Debye length for holes, given as

$$L_D = \sqrt{\frac{\varepsilon_s}{q p_{po} \beta}} \tag{3}$$

The applied capacitor voltage (V) appears across mainly three places (neglecting the band bending in the metal side): across the band bending region in semiconductor (φs), across the oxide layer (Vox), and the flat band voltage (V_{FB}).

$$V_G = \varphi_s + V_{ox} + V_{FB} \tag{4}$$

The voltage drop across the oxide layer (Vox) is related to the space charge in Si (Qs) and oxide capacitance (Cox = εox/d) as follows.

$$V_{ox} = Q_s/C_{ox} \tag{5}$$

For the sake of simplicity, the flat band voltage (V_{FB}) is merely determined by the difference of metal and semiconductor work function. However, as mentioned in eq. 1, Fermi level of graphene varies depending on the carrier modulation, ns. Equation (S1) is recast as follows.

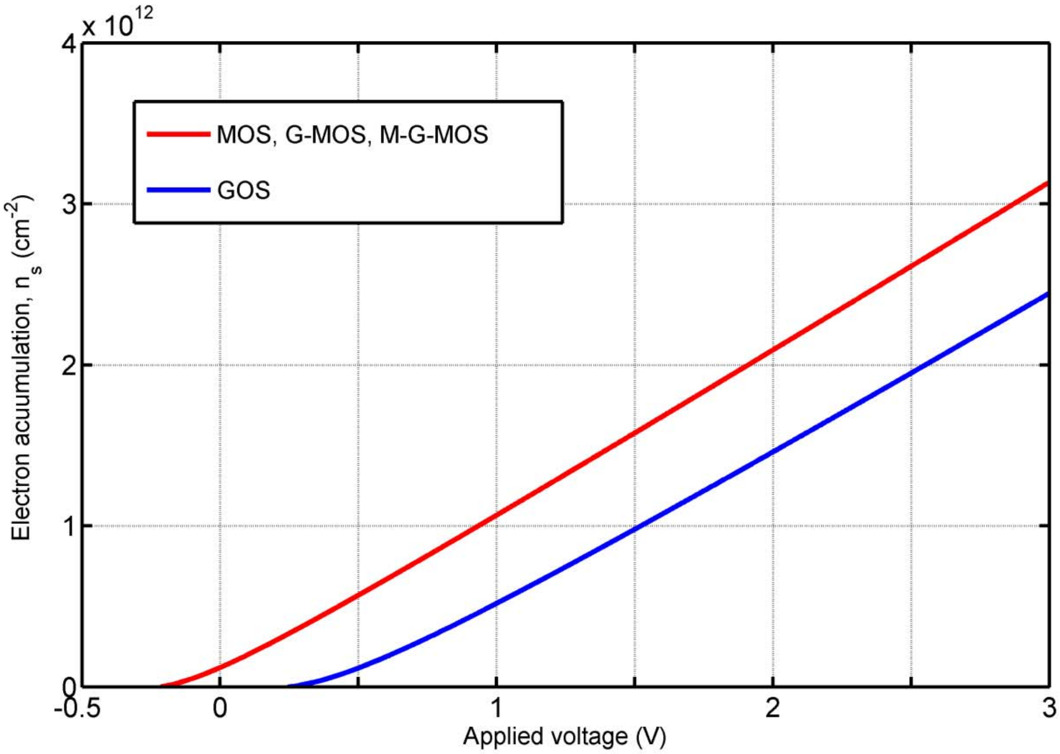
For MOS, G-MOS, M-G-MOS:

$$V_G = \varphi_s + V_{ox} + V_{FB} \tag{6}$$

For GOS:

$$V_G = (\phi_{G\_\mathrm{int}rinsic} \pm \Delta E_F) - \phi_s + \left|\frac{Q_S}{C_{oxide}}\right| + \varphi_S \tag{7}$$

Solving the above equations (1)-(7) simultaneously, the space charge density Qs can be calculated as a function of applied voltage V



Supplementary Fig. 4. Electron density, n_s (cm^{-2}) versus Applied voltage, V in the range of 0 to 3 V. Four different top electrodes on SiO_2/n-Si substrate were calculated: Al only, graphene only, graphene/Al, and Ga/graphene/Al. In this calculation, the following numbers were assumed: the work function of Ga, 4.3 eV; electron affinity of Si, 4.15 eV; electron affinity of SiO_2, 0.95 eV; dielectric constant of SiO_2, 3.9; dielectric constant of Si, 11.8 [S3]. The work function of Ga-covered graphene is expected to be similar to graphene's, but slightly reduced (to ~4.43 eV) due to the contact with Ga, which has smaller work function than graphene [S5, S6].

Supplementary References

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