Towards Vacuum-Less Operation of Nanoscale Vacuum Channel Transistors

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Introduction
Nanoscale Vacuum Channel Transistors (NVCTs) could potentially have superior performance compared to solid state devices of equivalent channel length owing to ballistic transport of electrons, shorter transit time and higher intrinsic breakdown voltage [1, 2]. The electron transport channel in NVCTs is free space and hence there is no scattering. Furthermore, there is no opportunity for ionization or avalanche carrier multiplication and NVCTs can have very high breakdown voltage [1]. Hence NVCTs have promise for Johnson figure of merit that could be as high as 10^{14} V/s. However, they need ultra-high vacuum (UHV) for reliable operation as the field emission process is sensitive to barrier height variations induced by adsorption/desorption of gas molecules. Small changes in the barrier height lead to exponential variations in current [3]. Poor vacuum also leads to generation of energetic ions that bombard the emitter tips, rendering the tips blunt and degrading electrical performance. To overcome the UHV requirement, we propose using graphene to nano-encapsulate only the field emitter either in UHV or in a gas (e.g. helium) with high ionization energy. By separating the field emission region from the acceleration region (where the electrons acquire energy), electrons can be transported in a non-ideal vacuum, if not atmospheric conditions. For mechanical strength, multiple graphene layers that are transparent to electrons while impervious to gas molecules/ions must be used [4–6]. In this work we demonstrate the electron transparency of multiple graphene layers.

Experimental Process
Si field emitter arrays (FEAs) reported in Ref. [3] (100 × 100 array) with 1 μm pitch, aperture diameters of ≈ 350 nm and integrated Si nanowire current limiters are fabricated as shown in Fig. 1. Current-voltage (I-V) characteristics of devices in UHV (10^{-9} Torr) are first measured in a triode configuration. Graphene layers are characterized by Raman spectroscopy with a laser wavelength of 532 nm. Intensity ratios of the 2D to the G peak (I_{2D}/I_G) measured for mono-, bi-layer and multi-layer were 1.43, 0.82 and 0.48 respectively (Fig. 2). Graphene layers suspended on holey (2.5 μm diameter and 4 μm pitch) 200 nm thick silicon nitride with 0.5 mm by 0.5 mm square area grids (TedPella Inc. Redding, CA, USA) are mounted on a probe with vacuum-compatible conductive Ag epoxy. The grids were mostly covered by the graphene with only sparse unavoidable punctured holes through the sheet as shown in scanning electron microscope (SEM) images (Fig. 2). Electrical measurements with the grid/graphene structure between the emitter and anode are repeated for gate-emitter voltages, V_{GE}, of 0-45 V and grid voltages, V_{Grid}, of 0-200 V.

Device Results
The Si FEAs turn on at V_{GE} ≈ 20 V and anode currents, I_A ≈ 5 μA are measured at V_{GE} = 45 V as shown in Fig. 3a. The high anode to emitter current ratio (I_A/I_E ≈ 0.97) and low gate to emitter current ratio (I_G/I_E ≈ 0.03) indicate the majority of electrons are collected at the anode. Fowler-Nordheim coefficients b_{FN} of 460 and log(a_{FN}) of −9 are extracted for both the anode and the emitter (Fig. 3b). Output characteristics shown in Fig. 3c demonstrate that Si FEAs exhibit transistor-like behavior in vacuum. In the presence of the grid and the graphene (Fig. 4a), V_{ON} shifts from 20 V to approximately 30 V and the current collected at the anode is one order of magnitude smaller. The maximum ratio (19%) of anode current to the current without graphene was observed at V_{GE} ≈ 42 V as shown in Fig. 4c. Using a grid alone, we obtained approximately 45% electron transmission at 0 V consistent with the open areas of the grid (39%). However, the grid material (Si_{3}N_{4}) is electrically insulating, causing charge accumulation and the resulting shielding effect decreases the effective transmission of electrons through the grid apertures.

Significance
We demonstrated electron transparency of ≈ 20% using an energized multi-layer graphene/grid structure. With an optimized design, we envision electron transparencies close to 100%. Adopting this structure as a nano-encapsulation architecture will enable high frequency (THz regime) compact NVCTs that are stable and reliable while being able to work in relatively poor vacuum. It will allow the realization of empty state electronics capable of functioning at higher power and harsher conditions (high radiation and high temperature) compared to solid state electronics.

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Fig. 1: (a) Schematic of Si FEAs with integrated current limiter and self-aligned gates; (b) cross-section image of an emitter after oxide stripping; and (c) emitter array fabricated with 1 μm pitch and 350 nm aperture diameter.

Fig. 2: Raman spectra of graphene layers on the nitride grid with the D, G and 2D peaks. SEM micrographs on the right for each type of graphene with the reduction in the intensity ratio from a single layer to multi-layers.

Fig. 3: (a) I-V characteristics of 100 by 100 arrays of Si FEAs measured; (b) Fowler-Nordheim plots of the currents with extracted slopes and intercepts; and (c) output characteristic measured with increasing $V_{GE}$ from 22 V to 30 V.

Fig. 4: (a) Schematic of the measurement set-up with the graphene on the nitride grid; (b) I-V characteristics of devices with multi-layer graphene biased at different voltages; and (c) anode current ratio of multi-layer of graphene to no grid/graphene case, with inset showing the percentage transmission through the structure.