Contact Resistance of Graphene-Based Devices by TLM

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Introduction:

Graphene is a 2D allotrope of carbon atoms arranged in a planar, hexagonal lattice. It features useful electronic properties [1] including bipolarity, high purity, high mobility, and high critical current density. Bipolarity refers to its ability to transport charge using either electrons or holes; the carrier type can be controlled by applying a gate voltage which shifts the Fermi energy. Graphene's high purity, mobility, and critical current density reflect its reliability and accessibility, its responsiveness to electric fields, and its resistance to breakdown. Hence graphene is considered a promising material for future electronic devices.

Crucial to the realization of feasible graphene devices are metal-graphene connections with low contact resistance. Contact resistance is the portion of total resistance attributed to the metal lead or its connection to the graphene, as opposed to the graphene itself. Initial studies [2] have informed us that contact resistance is a significant portion of total resistance. Prior work is inconclusive, some reporting that contact resistance is gate-independent [2], but others reporting both gate independent and dependent contributions [3].

We were interested in the relation of contact resistance to carrier type and to sheet resistance. We tested basic graphene transistors which consisted of metal contacts connected to each side of a rectangular graphene strip separated from the gate by a substrate. Figure 1 is a top view optical image of a sample with many devices where the black leads make contact with the darker gray graphene strips of varying length. Here, we examined titanium/gold (Ti/Au) contacts as a starting point because they are most common.

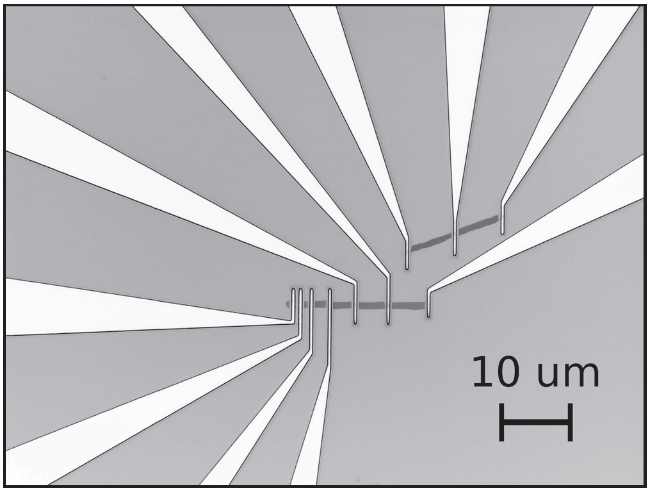

Figure 1: Graphene device with leads.

Experimental Procedure:

Fabrication. We deposited graphene, originating from Kish graphite, by exfoliation onto an silicon/silicon dioxide (Si/Si0$_2$) substrate. We used the electron beam lithography system to expose the graphene etch pattern into poly(methyl methacrylate) (PMMA) resist atop an hexamethyldisilazane (HMDS) adhesion layer. Reactive ion etching (RIE) with oxygen plasma removed the excess graphene such that only rectangular strips remained. We dissolved the protective resist layer with n-methyl-2-pyrrolidone (NMP) at 80°C.

Next, we fabricated metal contacts in two stages. First, we placed metal leads, separated by half and whole micron intervals, along the graphene strips. We used e-beam lithography to transfer the lead pattern to a PMMA bilayer (PMMA atop MMA/MAA EL12), e-beam evaporation to deposit Ti/Au, and lift-off in NMP to produce the leads. Second, we extended the metal leads with metal pads that were large enough to be accessed by macroscopic electrical probes. We used the laser lithography system to pattern a PMGI SF9 and TSMR8800 photoresist bilayer, the sputtering system to deposit metal, and NMP for lift-off. Finally, the devices were annealed at 300°C for 5 min in Ar.

Characterization. The transfer length measurement (TLM) method regards total resistance, R_T, as having two terms, according to Equation 1.

$$R_T = \frac{R_S}{W_{ch}} d + 2R_C$$

Equation 1: Total resistance as a function of lead separation.

The first term is directly proportional to d, the separation between leads, and accounts for the contribution to resistance from the graphene sheet (R_S is sheet resistance and W_{ch} is channel width). The remaining term is twice the contact resistance, R_C, representing the resistance from the two contacts per device. We report measurements for both contact resistance, R_C, and transfer length, L_T. Transfer length is the distance the current flows through the graphene below the contact and is another indicator of contact quality. L_T is approximately equal to half the horizontal intercept and R_C to half the vertical intercept of an R_C versus d line. The contact resistivity, ρ_c, is equal to the sheet resistance multiplied by the transfer length squared.

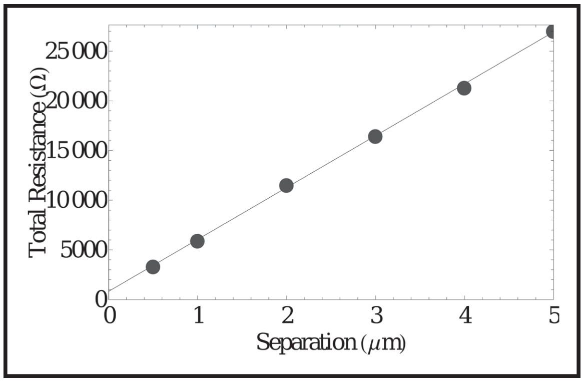

Figure 2: Total resistance versus lead separation.

Upon completing the fabrication of a device, we first verified that the contacts were ohmic, that is, that the drain current was directly proportional to the drain voltage. Then, we varied the gate voltage (thus changing the carrier type) and measured the total resistance. This measurement yielded a peak-shaped curve where the maximum resistance occured at the Dirac point, the point at which carrier type changes. For each lead separation, we recorded resistance at the Dirac point and at ± 10 volts to either side. We fit a line to a graph of total resistance versus lead separation (see Figure 2), from which we extracted contact resistance and transfer length following Equation 1.

Results and Conclusions:

The TLM analysis suggests that contact resistance is independent of carrier type. In addition, we find that both contact resistance and specific contact resistivity are independent of sheet resistance (the two-dimensional analogy to resistivity). Figure 3 plots contact resistivity, ρ_c, versus sheet resistance where green squares indicate data taken at the Dirac point and triangles indicate data taken for holes and electrons. The majority of our devices feature ρ_c values on the order of 10^{-6} $\Omega \bullet cm^2$ or less, which is one order of magnitude lower than previously reported values for ρ_c in graphene devices [2].

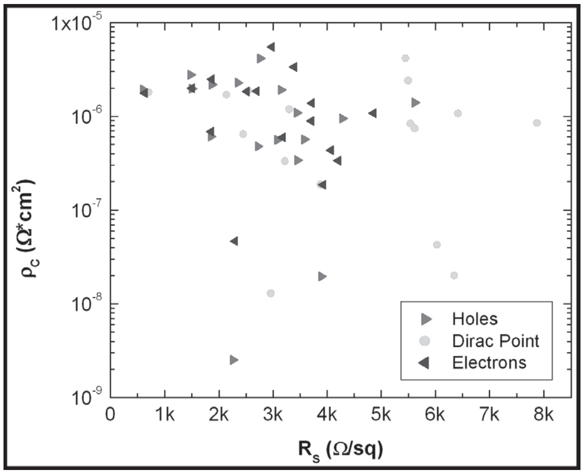

Figure 3: Contact resistivity versus sheet resistance.

Future work will involve testing a variety of types of metals as contacts in order to determine the dependence of contact resistance on variables such as metal work function. This property is of particular interest because [4] has already demonstrated that, in the case of carbon nanotubes, contact resistance is dependent on the metal's work function.

Acknowledgments:

I would like to acknowledge the National Nanotechnology Infrastructure Network Research International Experience for Undergraduates (NNIN iREU) Program and the National Science Foundation (NSF) for funding. I would also like to thank the National Institute for Materials Science (NIMS) in Tsukuba, Japan, for hosting me, especially Dr. Yasuo Koide (group leader) as well as Dr. Eiichiro Watanabe and Dr. Daiju Tsuya (mentors).

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