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Width Dependent Transport in Multilayer Graphene Interconnects: Exploring Ways to Reduce Resistance

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Abstract

The resistance of multilayer graphene interconnects was investigated experimentally with a focus on the edge effect. We observed an increase in resistance in narrow (25-600 nm-wide) graphene interconnects caused by edge scattering. Various promising ways to reduce this resistance are discussed.

1. Introduction

As LSI interconnects are miniaturized, higher resistivity of metal inteconnects is becoming problematic. Graphene is an attractive alternative material for interconnects because its high crystallinity provides a low grain-boundary-scattering rate and tolerance to electromigration. In addition, transport via edge states [1] is expected to give conductance that is independent of width [2], and thus provide narrower interconnects. However, the edges can also be a dominant scattering source in narrow interconnects.

2. Experimental

To examine the effects of the edges in graphene interconnects, we fabricated multilayer narrow graphene wires (Fig. 1) using high-crystallinity Kish graphite as a starting material. We prepared 10–48 nm-thick multilayer graphene flakes by using mechanical exfoliation [3]. The flakes were patterned into 25–600 nm-wide and 1-2 μm-long wires by electron beam lithography to form a SiO_2 mask and by oxygen reactive ion etching (RIE). Electrical resistance of the wires was measured at room temperature in a four-terminal configuration, as shown in Fig. 1.

3. Results

Resistance per unit length per graphene layer is plotted in Fig. 2 as a function of wire width. The resistance is proportional to $1/W$ (W: wire width) for wide wires (W > ~100 nm) and to $1/W^{2.5}$ for narrow ones (W < ~100 nm). The former gives constant resistivity of 47 μΩ·cm which is similar to bulk resistivity of graphite [4]. The resistivity corresponds to sheet conductance per graphene layer, $\sigma = 7.1 \times 10^{-4}$ S, which is converted to a product $k_F\lambda = 19$ (k_F: Ferimi wave vector, λ: mean free path) by a relationship $\sigma = (e^2/h)k_F\lambda$. The $1/W^{2.5}$ rule accords well with a theoretical model [2] without taking into account conduction via the edge state. In the model, the mean free path is dominated by edge scattering and conductance is determined by the Fermi level (E_F) and the probability (P) of back scattering at edges. The edges were not well controlled in our experiment because the edges were formed only by an RIE process [5, 6]. We speculated the edge scattering is diffusive, i.e., P = 0.5. We obtained E_F = 40 meV by fitting to the width dependence of the resistance. Using the Dirac dispersion $E_F = \hbar c k_F$ ($c = 1 \times 10^6$ m/s) with the assumption that the Fermi level is independent of W, we extracted λ for the wide width region to be 300 nm. Thus, the transition from the $1/W$ rule to the $1/W^{2.5}$ is consistent with the intuitive idea that the edge scattering becomes dominant when the width of the wire is narrower than the bulk mean free path dominated by defects and phonon scattering. We could not find a width independent conductance at a region with a narrow width, which means that the edge states did not make a significant contribution to the electronic conduction.

4. Discussion

For practical use, the resistivity of several tens of μΩ·cm is required. Thus, the resistivity of bulk graphite have to be kept even for W < ~10 nm.

We are investigating three ways to reduce the resistivity. The first way is to induce carriers, i.e., to increase E_F. We estimate the required E_F to be ~1 eV using the edge scattering model with P = 0.5 [2] if we do not take into account conduction via edge states. The second way is to make the edges smooth to reduce P. In a chemically-derived ultra-smooth graphene nanoribbon, a resistivity of several tens of μΩ·cm was obtained with carriers induced by field effect even for W ~ 2 nm [7,8]. Thus, the required resistivi-

ty has been obtained experimentally with a smooth edge and an increased E_F. The third way is to make zigzag edges for edge state conduction as described in Ref. [2].

For practical interconnects, it is difficult to apply external-voltage to induce carriers as a result of the field effect. Thus, we have to make a built-in mechanism to induce carriers. Using multilayer graphene provides lower resistance, but carriers can be induced in only a few layers from the surface [9]. If we use graphite intercalation compounds (GICs) instead of multilayer graphene, we can induce carriers densely up to $E_F \sim 1$ eV [10]. In some GICs, lower resistance than copper has been reported [11, 12]. We are developing the use of GIC as interconnects and have obtained resistivity under 10 μΩ·cm in mechanically exfoliated graphite flakes intercalated by bromine.

3. Conclusions

We investigated the width dependence of the resistance of multilayer graphene wire with edges formed by an RIE process. When the width of the wires was below ~100 nm, a higher level of resistivity was observed. The width dependence suggests that the edge scattering is a limiting factor of the conductance. Inducing carrier and controlling edge are ways of reducing resistance for practical interconnects. To induce the carrier, we are developing an intercalation method and have obtained low resistivity comparable to metals in exfoliated graphite intercalated by bromine.

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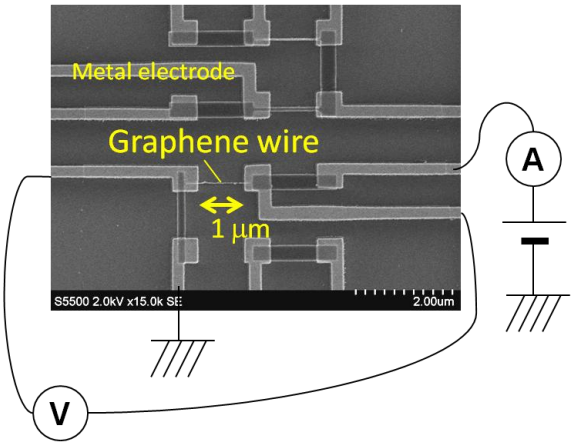

Fig. 1: SEM image of multilayer graphene wires and schematic measurement configuration.

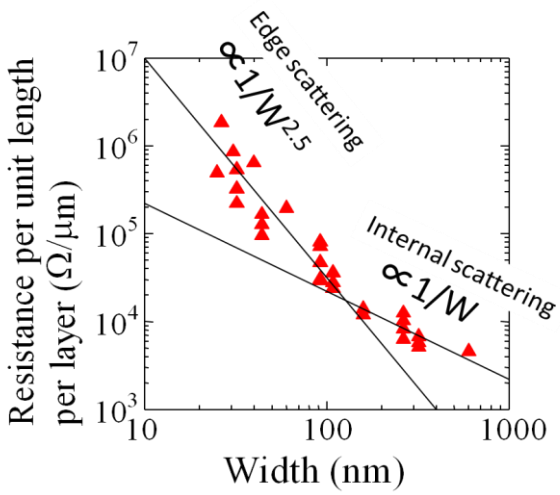

Fig. 2: Width dependence of resistance of multilayer graphene wires per unit length per layer.