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Resistivity of graphene nanowires: Requirements of quality and doping for interconnect applications

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Abstract

We experimentally and theoretically examined the resistivity of graphene nanowires. An increase of the resistivity in narrow wires agreed well with our calculation in which the edge scattering is taken into account. The quality and doping targets were evaluated in terms of the mean free path and the Fermi level based on the results from the calculation.

1. Introduction

Since LSI interconnects are now miniaturized, the need for higher resistivity of the metal interconnects is becoming problematic. Graphene or graphite is an attractive alternative material for use in these interconnects, because its conductivity is potentially higher than metal with an edge state transport [1] or doping by intercalation [2]. However, the quality of graphene and the doping level need to be enhanced in realistic production processes. Their requirements are quantitatively discussed in terms of the mean free path and the Fermi level in this paper.

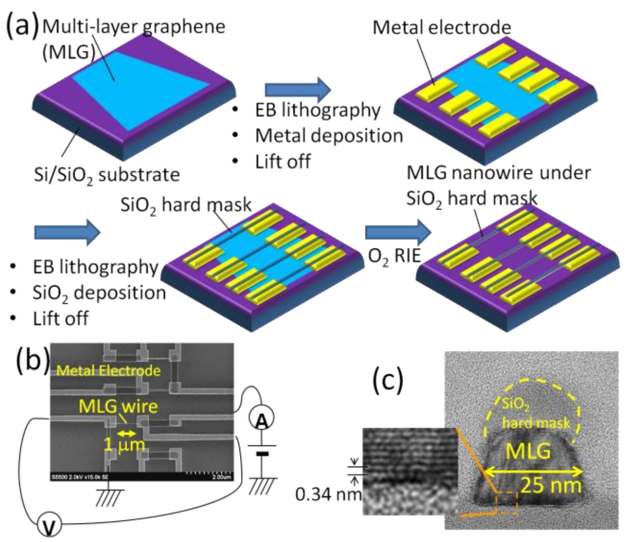

Fig. 1 (a) Procedure for fabricating MLG nanowires. A MLG flake is prepared on a Si/SiO_2 substrate using Kish or CVD graphite as the starting material. Electron beam lithography, deposition, and a lift-off process are used to form the metal (Ti/Au) electrodes and hard masks (SiO_2). O_2 RIE is used to remove the unnecessary MLG. (b) and (c) are SEM and TEM images of MLG nanowires.

2. Experimental

We fabricated multilayer graphene (MLG) wires using low-temperature-grown CVD graphene and high-quality Kish graphite as the starting materials (Fig. 1). Plasma-enhanced CVD at 600 °C was used to grow the CVD graphene (typically 20 nm thick) on a Ni catalyst layer (30 nm thick) [3]. The graphene layers were exfoliated from the Ni catalyst layers using a support layer and transferred onto SiO_2/Si substrates after growth [4]. The Kish graphite was transferred onto SiO_2/Si substrates using a mechanical exfoliation method [5], becoming 10–48-nm-thick MLG flakes. The MLG films were patterned into 16-nm–10-μm-wide and 1-2-μm-long wires by using electron beam lithography to form a hard mask and by using oxygen reactive ion etching (RIE), as shown in Fig. 1. The electrical resistance of the wires was measured at room temperature in the four-terminal configuration shown in Fig. 1(b).

3. Results and discussion

The resistivity of graphene wires is plotted in Fig. 2 as a function of the wire width W for both the CVD and the Kish graphene. The resistivity of the Kish graphene rapidly increases when it is less than 100-nm wide. The CVD

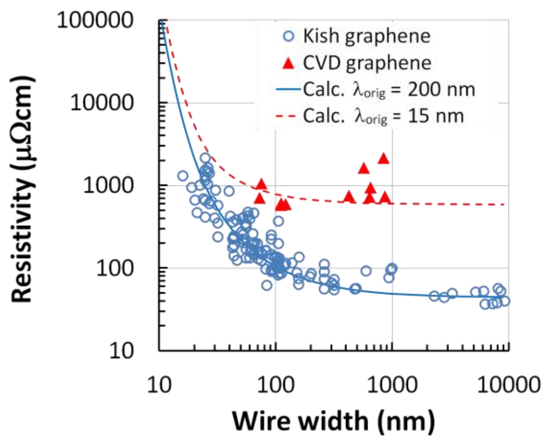

Fig. 2 Width dependence of resistivity for Kish (circles) and CVD (triangles) graphene. The curves represent the calculation results for λ_{orig}= 200 nm (solid) and 15 nm (dashed) using the common parameters E_F= 60 meV, P= 0.5, and T= 300 K.

graphene has a higher and less width-dependent resistivity.

We analyzed the width dependence of the resistivity by conducting a numerical calculation based on the Landauer's formula [6, 7]. The enclosure of the charge carriers in the wire quantizes the transverse wave number k_y with the index n: $k_y = n\pi/W$. The index n groups the electron states that form a one-dimensional band in longitudinal k-space (k_x). The conductance of the wire is determined by the weighted summation of the mean free path of each one-dimensional band. The weighting is determined by considering the Fermi level E_F and the temperature T via the Fermi distribution. We take into account two scattering components, the edge scattering and internal scattering, for the mean free path. The edge scattering is parameterized by the back scattering probability at the edges (P) [8]. The internal scattering is related to the quality of the graphene and is parameterized by the "original" mean free path λ_{orig}, which is due to the scattering mechanisms not related to edges. Thus, the conductance is calculated using parameters, W, E_F, P, λ_{orig}, and T.

Since ordinal electron beam lithography and RIE are used to create the edges in our sample, we assume that the edge scattering is diffusive, i.e., P= 0.5. We obtained a good fitting to the experimental results by conducting a calculation using E_F= 60 meV and λ_{orig}= 200 nm for Kish graphene (the solid curve in Fig. 2). Assuming that the same P and E_F are used, the λ_{orig} of the CVD graphene is estimated to be 15 nm, which is one-magnitude shorter than that of the Kish graphene. The large difference in the λ_{orig} is inevitable, because of the different growth temperatures [9]. However, the difference due to λ_{orig} becomes small for a small W, as shown in the calculated curves in Figs. 2 and 3(a). This is because the edge scattering is more dominant than the internal scattering in narrow wires.

We would like to discuss the required levels of doping and quality in terms of E_F and λ_{orig} in order to determine the guidelines for improving the conductance of graphene interconnects. Here, we set the target resistivity at a few tens μΩcm at W= 10 nm, and the high quality limit to be that of Kish graphite (λ_{orig}= 200 nm). We do not take into account any contribution from the edge states of graphene nanoribbon [6, 10]. Even at the high quality limit, the required Fermi level is E_F= 1 eV (Fig. 3(a)). Such a Fermi level is typical for graphite intercalation compounds [2, 11]. With the Fermi level, a similar resistivity is predicted at the λ_{orig}= 50 nm, but not with the λ_{orig}= 10 nm. Roughly speaking, improving λ_{orig} is not as effective when the λ_{orig} ~> 5 W (Fig. 3(b)).

3. Conclusion

The experimental resistivity as a function of the width for graphene nanowires was well reproduced using a theoretical calculation. Using the calculation method, we extracted the target values E_F= 1 eV and λ_{orig}= 50 nm as levels of doping and quality for 10-nm-wide interconnects.

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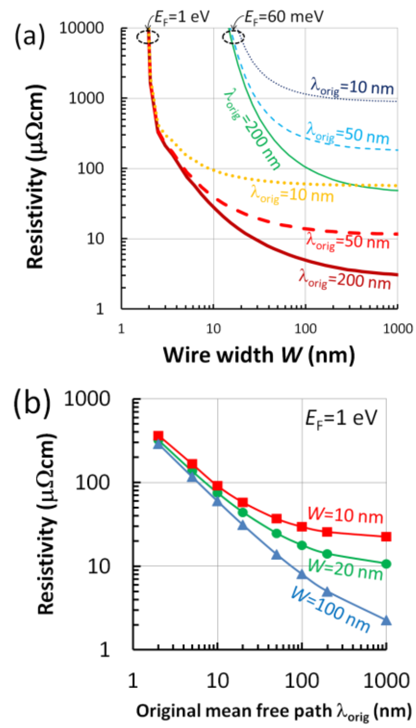

Fig. 3 Simulated resistivity for various λ_{orig} and E_F. (a) Resistivity as function of W for λ_{orig}= 10, 50, and 200 nm (dotted, dashed, and solid lines) with E_F= 60 meV (thin) and 1 eV (thick). (b) Resistivity as function of λ_{orig} for W= 10, 20, and 100 nm (rectangles, circles, and triangles) at E_F= 1 eV. The calculations were made using common parameters P= 0.5 and T= 300 K.