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DOS Bottleneck for Contact Resistance in Graphene FETs

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1. Introduction

Graphene-based devices are promising candidates for future high-speed field effect transistors (FETs) [1], where an increase in the on/off current ratio (I_{on}/I_{off}) is the biggest issue. We have so far paid attention to the contact properties as the performance killer [2,3]. Although a Schottky barrier is not formed at the graphene/metal interface, it is concerned that a very small density of states (DOS) for graphene might suppress the current injection from the metal to graphene. In this study, graphene FETs were fabricated by mechanical exfoliation of Kish graphite. We first reveal the current flow path at the graphene/metal contact. Then, the contact resistivities required for miniaturized graphene FETs are quantitatively assessed based on the contact resistivity obtained experimentally by the cross-bridge Kelvin (CBK) method. Finally, the graphene/metal contact is discussed from the viewpoint of metal work function of contact metals employed.

2.1 Current flow path at G/M contact

First, it is determined whether the contact resistivity (ρ_C) is characterized by the channel width (W) or by the contact area ($A=Wd$). **Figs. 1(a)** and **(b)** show the four-layer graphene device with six sets of 4-probe configurations (#1~#6). **Fig. 1(c)** shows the relationship between the contact area and two types of contact resistivities, $\rho_C=R_CW$ and $\rho_C=R_CA$, where R_C were extracted by the four-probe measurements. ρ_C ($=R_CA$) increases with an increasing contact area, whereas ρ_C ($=R_CW$) is nearly constant for all of the devices. This indicates that ρ_C is characterized by W, i.e., the current crowding takes place at the edge of the graphene/metal contact.

In reality, however, the current does not flow at the line along the contact edge; rather, it does in a finite area

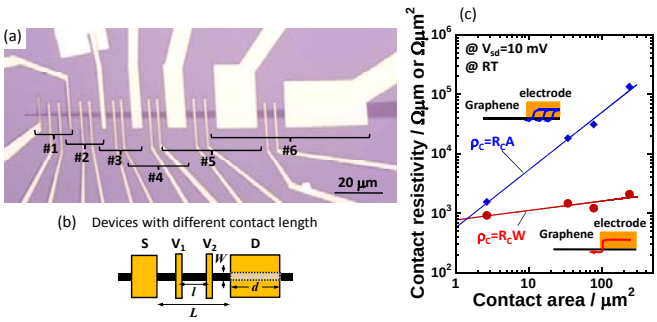


Fig. 1 (a) Optical micrograph and (b) schematic of the device. The contact metal is Ni. The devices with different contact areas for the source and the drain were fabricated, and the contact area for the voltage probes was kept constant to avoid uncertain effects from the voltage probes. (c) R_CA and R_CW as a function of contact area.

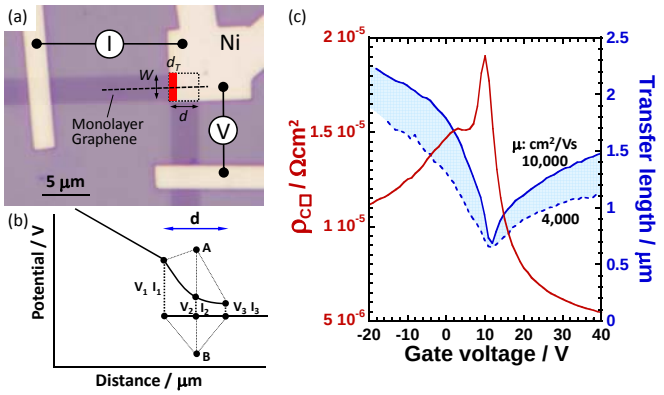


Fig. 2 (a) Optical micrograph of the cross-bridge Kelvin structure for the monolayer graphene. (b) Schematic of the potential along the dotted line in (a). The voltage between A and B is measured. (c)$\rho_{C\square}$ and d_T as a function of the gate voltage.

in which most of the current are injected from the metal to graphene. To account for the current crowding in more detail, the effective contact distance, known as the transfer length (d_T), is considered based on the transmission line model (TLM) [4]. d_T is defined by the relative magnitude of R_{ch} and $\rho_{C\square}$ as $d_T = \sqrt{\rho_{C\square} / R_{ch}}$.

Hereafter, the graphene/metal contact is more accurately referred by using both $\rho_{C\square}$ and d_T instead of the edge-normalized ρ_C. To quantitatively measure $\rho_{C\square}$, the CBK structure [5] was used, as shown in **Fig. 2(a)**. A constant current was flown between two electrodes on the upper side, and then the voltage was measured between the two electrodes on the right side as shown in **Fig. 2(b)**. $\rho_{C\square}$ can be directly determined by, $R_C = V / I \sim \rho_{C\square} / dW$ (d >> d_T).

Fig. 2(c) shows $\rho_{C\square}$ and d_T as a function of the gate voltage (V_g). $\rho_{C\square}$ is ~5×10^{-6} Ωcm^2 at a high gate voltage, and d_T is shown as a function of V_g by considering both high and low mobility cases. The sheet resistivities measured previously [3] for both low and high mobility cases were used for estimating d_T. The contact length in the device shown in **Fig. 2(a)** is ~4 μm, but only ~1 μm is effective for the current transfer. In **Fig. 1(c)**, ρ_C was roughly determined by the edge, because the contact lengths in the device are much longer than d_T. Therefore, if the contact length becomes shorter than d_T, a transition from the edge conduction to area conduction will occur.

2.3 $\rho_{C\square}$ required for short channel G-FETs

Next, we discuss the $\rho_{C\square}$ value required for miniaturized graphene FETs. The condition required for $\rho_{C\square}$ has been taken as the ratio of R_C with R_{sh} should be less than 10%, as shown by the equation ,

$R_C / R_{ch} = \sqrt{\rho_{C\square} / \rho_{ch}} / L < 0.1$, where L is the channel length. **Fig. 3** shows R_C/R_{ch} as a function of $\rho_{C\square}$ for various L. In this calculation, a typical value for ρ_{ch} = 250 Ω at 5×10^{12} cm^{-2} was used. For the channel length of 10 μm, the present status of $\rho_{C\square}$ satisfies the requirement by employing Ni. For the channel length of 100 nm, however, the required $\rho_{C\square}$ value is less than 10^{-9} Ωcm^2, which is four orders of magnitude lower than the present status. This value is smaller than that required for the metal/Si contact (~10^{-8} Ωcm^2) because the R_{sh} of graphene is lower than that of Si.

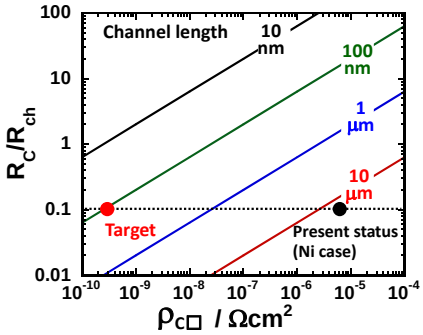


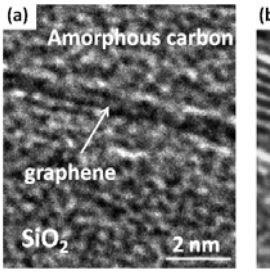
Fig. 3 Relationship between $\rho_{C\square}$ and R_C/R_{ch} for various channel lengths.

2.3 Physical & Chemical analysis of G/M interface

The typical contact resistivities ($\rho_C = R_C W$) for the different contact metals Cr/Au, Ti/Au and Ni are ~10^5, ~10^4, and 500 Ωμm, respectively. Noted that they are shown by edge-normalized ρ_C. This suggests that the selection of the contact metal is crucially important since the high mobility of graphene might be obscured by the high contact resistance.

The graphene/metal contact is further considered form the physical and chemical viewpoints to understand the large difference in contact resistance for the sorts of metals. **Fig. 4** shows X-TEM images for both (a) mono-layer and (b) 9-layers graphene films. The layered structure just below Cr as well as monolayer covered by amorphous carbon is clearly observed. This physical analysis shows no deterioration at the metal/graphene interface.

For the chemical analysis, the X-ray photoelectron spectra were analyzed for Ni and Cr thin films deposited on highly oriented Pyrolytic graphite (HOPG) at the base pressure of 5×10^{-6} Pa. By iterative Ar ion etching, the thickness dependence of spectra was collected as shown in **Fig. 5**. By thinning the metal films, the Ni peak was only detected and did not shift, while the oxidation state of Cr was observed as the shoulder of the Cr peak. Although suboxides may exist at the HOPG/Cr interface, a distinct oxide layer is not detected, which suggests that the oxide layer formation is not the reason for high $\rho_{C\square}$.



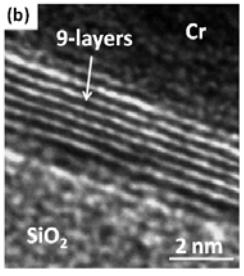


Fig. 4. X-TEM images for (a) monolayer and (b) 9 layered graphene on SiO_2. The top surface of monolayer is fixed by amorphous carbon.

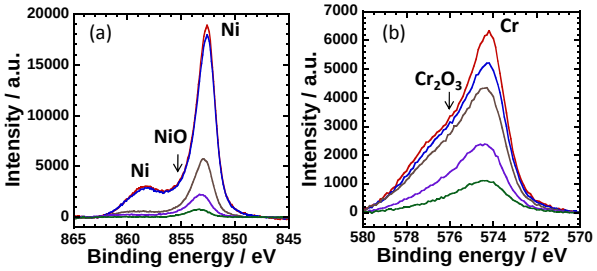


Fig. 5 (a) Ni 2p and (b) Cr 2p photoelectron spectra. The peak intensity decreased with decreasing the thickness of metals.

Finally, the factors that determine $\rho_{C\square}$ should be considered in order to further decrease $\rho_{C\square}$ by four orders of magnitude. The ideal graphene/metal contact is assumed since the chemical shift and obvious oxidation state were not detected in photoelectron spectra. Thus, the work function difference (Δϕ) between graphene and metal is focused on. The work functions of graphene, Ti, Cr, and Ni are 4.5, 4.3, 4.6 and 5.2 eV, respectively. It is clear that Ni, which has the largest Δϕ, also has the lowest $\rho_{C\square}$. For the case of a larger Δϕ, the electron is transferred from the graphene to the metal, which considerably increases the DOS in graphene under the metal contact and reduces $\rho_{C\square}$, as schematically shown in **Fig. 6**. Therefore, to obtain the low $\rho_{C\square}$, the metal with a larger Δϕ is preferred.

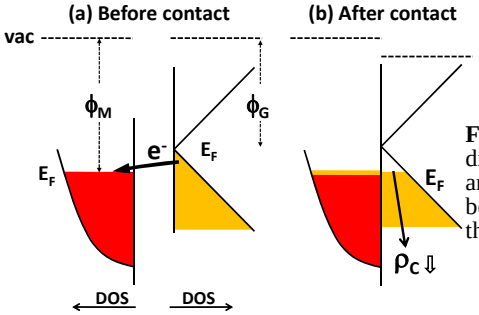


Fig. 6 Energy-DOS diagrams for metal and graphene. (a) before and (b) after the contact.

3. Conclusions

In summary, the contact resistance will be a limiting factor against the scaled graphene FETs because the $\rho_{C\square}$ should be lowered by several orders of magnitude from the present status of ~5×10^{-6} Ωcm^2. The systematic results suggest that metals with a higher ΔΦ may be preferred for achieving the low $\rho_{C\square}$ thanks to an increase in the DOS of graphene underneath the metal by the charge transfer.

Acknowledgement We are grateful to Dr. E. Toya in Covalent Materials for kindly providing us Kish graphite. **References** [1] A.K. Geim, et al., Nature Mater. **6** (2007) 183. [2] K. Nagashio, et al., IEDM Tech. Dig. (2009) 565. [3] K. Nagashio, et al., JJAP **49** (2010) 051304. [4] D. K. Schroder, in Semiconductor material & Device characterization, Wiley interscience, 2006, 138. [5] S. J. Proctor, et al., IEEE Electron dev., **30** (1983) 1535.