Extraction of Graphene-Titanium Contact Resistances using Transfer Length Measurement and a Curve-Fit Method

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Abstract—Graphene-metal contact resistance limits the performance of graphene-based electrical devices. In this work, we have fabricated both graphene field-effect transistors (GFET) and transfer length measurement (TLM) test devices with titanium contacts. The purpose of this work is to compare the contact resistances that can be numerically extracted from the GFETs and measured from the TLM structures. We also provide a brief review of the work done in the field to solve the contact resistance problem.

Keywords—Contact resistance, graphene, TLM

I. INTRODUCTION

GRAPHENE is a hexagonally-organized form of carbon atoms that is only one atomic layer thick [1]. It is the thinnest material known to man so far, and the atomic structure gives rise to exceptional electrical, optical, mechanical and thermal properties [2]. The most interesting electrical properties are high electron mobility and ballistic transport of charge carriers.

Graphene field-effect transistors utilize mono- or few-layer graphene as channel material. Graphene displays an ambipolar field effect that can be explained with the bandstructure [1]. An applied electric field induces doping in graphene by changing the Fermi energy which is an effect often referred to as self-doping. Self-doping allows the charge carrier type and concentration to be controlled with an outside electric field, or rather with a gate voltage. Graphene is a semimetal which means that it has no band gap. This results in poor on/off ratio for current. The lack of a band gap in intrinsic graphene is, together with large scale manufacturing, one of the most challenging problems for electronics. Having no band gap is a problem if graphene is to be used in logic circuits in much the same way as silicon is used today as the material for CMOS logic circuits [3]. Nonetheless, there are applications where the trade-off between high power consumption and high performance is negotiable. One such example is radio frequency (RF) applications.

Although, GFETs show promise for RF applications, there is one obstacle in the way, the graphene-metal contact resistance. The contact resistance of the metal-graphene junction should be as small as possible. Reducing contact resistance is crucial especially in GFETs with very short channels, because high contact resistance may otherwise limit the operation by lowering the cut-off frequency. The contact resistance of graphene/metal interface has not received much attention, and results are sometimes contradictory. For example, Venugopal et al. [4] propose that contact resistance is independent of gate voltage, whereas many others have observed that contact resistance does depend on the gate voltage [5]–[7].

In this paper, we have fabricated and measured GFETs and TLM test devices to investigate the graphene-titanium contact in room temperature. Moreover, we have compared the numerical curve-fitting method and the TLM measurement results to investigate the accuracy of a curve-fit method for circuit design modelling purposes. In Section II, the formation of the metal-graphene junction is discussed and background information is given. The measurement methods are explained in Section III and in Section IV, we discuss the results. Section V concludes the paper.

II. GRAPHENE CONTACT RESISTANCE

The intrinsic performance of graphene transistors is masked by the high contact resistance. Contact resistance is currently the major electric current limiting factor in GFETs [4]. The contact resistance limits the cut-off frequency, the transconductance and the current-gate voltage linearity of field-effect transistors.

The contact resistance, $R_c$, can be defined as the sum of the resistances of the physical metal interconnects, the metal-graphene interface (interfacial resistivity) and the ungated channel between contact and the transistor (access resistance). The contact resistance in a graphene transistor is illustrated in Fig. 2. The parasitic contact resistances are in series with the graphene channel resistance. As the specific contact resistivity is a combination of several phenomena, such as interfacial...
resistivity, it cannot be predicted from theory. Theory is able to predict interfacial resistivity, which unfortunately cannot be measured directly [8].

The collected contact resistances from the recent articles are shown in Table I. Table I shows that there is a large variation between the contact resistances. Several studies show that graphene/metal $R_c$ depends on the gate voltage with a maximum value at low gate voltages and minimum at high gate voltages [5]–[7]. The contact resistance in graphene/metal contacts is found to be dominated by a gate voltage independent part. The most probable explanation currently offered, is due to significant charge transfer at the graphene/metal interface shifting the Fermi level of the graphene far away from degeneracy point [7]. It is suggested that only the top layers in a graphene stack contribute to contact formation [4] [5]. The gate voltage independent part of $R_c$ has been found to correlate with the background pressure during processing with lower pressure resulting in lower $R_c$ [7]. This is believed to be related to adsorption of molecules prior to evaporation or the oxidation of the metal layer during deposition.

The current flow path at graphene/metal contact is through the edge i.e. current crowding takes place at the edge of the contact [5]. The transition from edge conduction to area conduction takes place for a contact length shorter than the transfer length 1 $\mu$m for Ni/graphene contact [5]. Transfer length is a quantity describing the distance over which most of the current (1/e) is transferred from the semiconductor to the metal or vice versa. The transfer length is described as

$$L_T = \sqrt{\frac{\rho_c}{R_{sh}}}$$

where $\rho_c$ is the specific contact resistivity and $R_{sh}$ is the sheet resistance of graphene [8]. Transfer length is a property of the system and is dependent on which metal is used.

More importantly, the recent studies show that the choice of contact metal is crucial for the device performance. Table II shows the work functions for several metals. It has been observed experimentally that high work function difference between graphene and the metal results in lower contact resistance [5]. Typically a great difference between metal/semiconductor work functions predict a high contact resistance. It is understood that for the case of a large difference in work functions, the electron is transferred from metal to graphene increasing the density of states in graphene under the metal contact and thus reducing the specific contact resistance [5].

One practical model of GFET total device resistance presented by Kim et al. [10]. The model describes the total device resistance as a function of top gate voltage ($V_{TG}$) and consists of three equations:

$$n_{tot} = \sqrt{n_0^2 + n[(V_{TG} - V_{DRC})]^2}$$

$$V_{TG} - V_{DRC} = \frac{qN_{ox}}{C_{ox}} + \frac{h\nu_F}{q} \sqrt{\frac{\pi n}{\mu}}$$

$$\hat{R} = R_c + R_{channel} = R_c + \frac{N_{sq}}{n_{tot}q\mu}$$

where $n_{tot}$ is the charge carrier concentration, $q$ is the elementary charge, $\mu$ is the conductivity mobility, $\nu_F$ is the Fermi velocity in graphene, $C_{ox}$ is the oxide layer capacitance, $\hat{R}$ is the predicted total device resistance, $R_c$ is the contact resistance and $N_{sq}$ is the number of squares. Eq. (2)-(4) allows an estimate of the contact resistance from a single current-voltage measurement, even though the effect of gate voltage on $R_c$ is neglected here.

### III. MEASUREMENT METHODS

Measuring contact resistance is complicated though the measurement itself is often simple. Different measurement strategies may easily lead to very different results and the interpretation of the results is complicated [8]. A well-known method to directly measure $R_c$ is the transfer length method (TLM) that should not be confused with transmission line model (also abbreviated TLM) used to characterize semiconductor sheet resistance and $R_c$ [8]. Both methods use a similar test device geometry, but transfer length method has more than three contacts. A schematic of the transfer length method test device is shown in Fig. 3 and a close-up of one actual device is shown in Fig. 1. There are altogether four test structures in the die we fabricated. The distances between contacts are 1, 2, 4 and 8 $\mu$m and the width, W, of each contact is 10 $\mu$m and the length, L, of the contact is 1 $\mu$m. Transfer length measurement is performed so that the total resistance is measured between adjacent contacts, e.g. in Fig. 3 the resistance is measured between A-D, D-B, B-E, E-C and C-F.

Another method to acquire $R_c$ is to extract the $R_c$ from total device resistance of a GFET by using Eq. (2)-(4). The total resistance is measured against the back or top gate voltage. This method was suggested in [4] and [10], though the former
The model described by Equations (2)-(4) was fit to the VI-measurement data of four GFETs of the same size and one different size GFET with nonlinear least squares curve fitting algorithm in Matlab. Optimization algorithm finds parameters that minimize the following cost function

$$J(x) = \sum_i (\hat{R}(x, V_{TG,i}) - R(V_{TG,i}))^2$$

where \(x\) is a vector containing the three unknown parameters: contact resistance \(R_c\), residual carrier density \(n_0\) and mobility \(\mu\). \(\hat{R}(x, V_{TG,i})\) is the total device resistance predicted by the model with parameters \(x\) and applied top-gate voltage \(V_{TG,i}\). The actual measured resistances are denoted with \(R(V_{TG,i})\). The operation of the curve-fit algorithm was evaluated with k-fold cross-validation with ten folds and three repetitions [11].

Fig. 5 shows the curve-fit results for a GFET with \(W=25\mu m\) and \(L=0.5\mu m\). Table IV shows the curve-fit results for GFETs. The variation in the GFET properties is evident in Table IV. The back gate voltage is 0V. The GFET with the lowest value of \(R_c\) in Table IV has the highest mobility, as is expected.

The contact resistance values from the curve-fit algorithm were normalized to be comparable to the TLM measurement. It was assumed that the drain contact has much larger contact resistance, and the contact area was determined by the drain contact. The results of the curve-fit after the normalization reference provides validation of the suggested method with transfer length measurement. Equations (2)-(4) can be used to extract contact resistance from a single measurement through curve-fitting. Similarly, according to [4], \(R_c\) can be retrieved from \(V_{TG} - R_{Total}\)-curve in the high gate voltage limit. A rough estimate of \(R_c\) is the ‘tail’ of the total resistance curve at the high voltage limit.
V. CONCLUSION

The operation of GFETs is limited by the low current on/off ratio and high contact resistance, as well as the defects and impurities in the graphene. Graphene-metal contact resistance has gradually gained more attention, and experimental results have been published. Yet, comprehensive theoretical explanations of the graphene-metal contact resistance are still missing. Moreover, predicting the contact resistance of any graphene-based device is currently missing.

The contact resistance of graphene-titanium-contact was investigated in this work using two methods, the transfer length method and a curve-fit method. The transfer length method requires separate devices to be fabricated. The curve-fit method applies for micrometer-size GFETs and does not require additional measurements or devices. Both methods give insight to the graphene-metal contact resistance, and as is to be expected, give different results for the contact resistance. For GFET circuit level modelling and design, the curve-fit method is practical, quick and gives a good estimation of the contact resistance. The contact resistance values from the transfer length measurement are in line with the state-of-the-art, yet for practical applications the GFET contact resistance needs to be improved.

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