# A large scale systematic study of graphene/metal contact resistance using cTLM

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## Abstract

In this work, a systematic study of the graphene/metal contact resistance ($R_C$) is conducted. The circular Transfer Length Method (cTLM) is used to determine the $R_C$ values with several metals. Samples with Cu, Ti, Ni, Pt, Ag, Pd and Au contacts were fabricated and electrically characterized. Our results indicate that noble metals show lower $R_C$. The lowest $R_C$ was observed for Au samples (~2.3kΩ.μm). Further improvement of contact is observed after a high temperature (300°C) anneal in Ar.

## Introduction

Graphene is one of the candidates for post-Si electronics. It is actively being investigated both for channel and interconnect applications. One common concern is contact engineering. The effect of the metal contacts on graphene and the contact resistance ($R_C$) values measured are important topics not only for graphene device performance but also for hybrid graphene/metal interconnects. Contact resistance has to be as low as possible. 80Ω.μm is the state-of-the-art demand in Si devices [1]. Ohmic contacts, without rectifying characteristics, are desirable. The voltage drop over the contact should be small, to provide enough current to the device [2]. Reported $R_C$ values show large scatter ranging from hundreds to tens of thousands Ω.μm. The results depend on the graphene type (exfoliated, CVD grown, epitaxially grown), the fabrication and post-fabrication treatments and the metal used. Apart from the metal work function, factors such as cleanliness, metal quality, wettability, grain size, roughness and edge vs. surface contacts may play a role [1, 3-7].

The aim of this work is to develop a systematic approach to process, characterize samples and analyze data. The goal is understanding and tuning the graphene/metal interface towards lower $R_C$ values.

## Experimental

In this work CVD (Chemical Vapor Deposition) grown graphene was used as it is the most suitable for large scale technological applications. Graphene was transferred onto a $Si/SiO_2$ substrate. To determine $R_C$, the circular Transfer Length Method (cTLM) [2, 8] was used with a series of different metals. As only one lithography step is required to deposit the metal contacts, cTLM is a fast and efficient method. Moreover, because of the circular configuration current spreading effects are limited.

cTLM structures were fabricated with photolithography on 2x2cm$^2$ graphene samples. An optical image of the fabricated structures is shown in Fig. 1. One structure consists of 12 circular electrode configurations (inner and outer) with electrode spacing ranging from 1μm up to 32μm. The radius of the inner electrode is 50μm. Special focus was given on collecting statistical data for every case, thus 72 cTLM structures were fabricated and characterized on the same sample.

cTLM samples were fabricated and electrically characterized with Cu, Ti, Ni, Pt, Ag, Pd and Au contacts. 50nm of metal were deposited for Cu, Ni, Pt, Pd and Au. 30 nm of Ti or Ag with a capping layer 20nm of Pd or Au were also investigated. Capping layers were used to prevent contact oxidation. The sample denoted (Ti)/Pd was fabricated with 1nm of Ti and 50nm of Pd. This metal stack was investigated as Ti is known to improve adhesion for Pd contacts.

$I_d$ - $V_d$ curves were measured at room temperature (25°C) using a Suss+MicroTec PA300 wafer prober and an Agilent 4156C parameter analyzer. Before measuring, all samples were annealed at 150°C in $N_2$ for 1 hour to reduce the effect of the ambient conditions. Based on the calculated total resistance and using the cTLM, contact and sheet resistance ($R_S$) values were extracted.

We have also investigated the effect of annealing at higher temperatures. Samples were annealed at 300°C in Ar for 1 hour before electrical characterization.

## Results and discussion

Average $R_C$ and $R_S$ values extracted for different metals are shown in Fig. 2a and 2b respectively. The average is performed on values from up to 72 structures. Error bars represent standard deviation. Noble metals such as Pt, Ag, Pd, Au show lower $R_C$ compared to Cu and Ti. Ni is the only non-noble metal that produces a contact resistance comparable to that of the noble metal. A possible explanation is metal oxidation at the interface with graphene. Further physical characterization of the interface is ongoing.

The lowest $R_C$ was observed for Au samples (~2.3kΩ.μm). Ti/Au (30nm Ti, 20nm Au) and

Ti/Pd (30nm Ti, 20nm Pd) samples resulted in similar $R_C$ values, this being an indication that the capping metal has no effect on $R_C$.

The comparison between (Ti)/Pd (1nm Ti, 50nm Pd) and Ti/Pd (30nm Ti, 20nm Pd) indicates that the contact degrades with a higher amount of Ti present. Most probably in the (Ti)/Pd case a Pd contact to graphene is effectively formed.

Extracted $R_S$ values (Fig. 2b) are approximately independent of the metal used. The average $R_S$ extracted is ~1.8kΩ.

In Fig. 3a and 3b the results of annealing at higher temperatures can be seen for Cu, Ti and Pd. In all cases large improvements in the extracted $R_C$ values were observed after annealing (Fig. 3a). The largest improvement of ~92% was observed for Cu. The $R_S$ values extracted (Fig. 3b) were approximately similar before and after annealing, indicating that the overall improvement comes from a reduced contact resistance.

## Conclusion

We have applied a systematic approach for comparing the contact resistance between graphene and several metals. We have used the same graphene type, fabrication conditions and characterization methods for all metals. To collect statistical data, we have performed measurements over large device sets. Our results indicate that noble metals show lower $R_C$. This suggests possible oxidation of non-noble metals at the interface with graphene. Annealing at 300$^{o}$C in Ar lowers the contact resistance values.

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## References

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## Figures

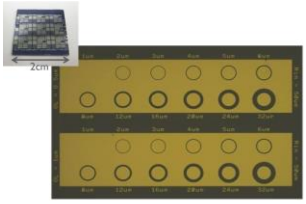

Figure 1. An optical image of the fabricated cTLM structures.

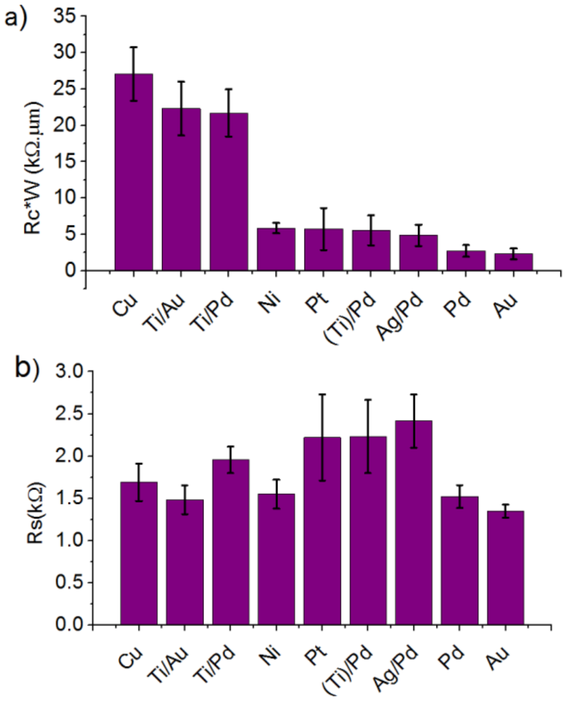

Figure 2. a) $R_C$ values extracted for various metal contacts. All noble metals show lower $R_C$ with Au samples showing the lowest (~2.3kΩ.µm). Samples with Ni contacts also have a low $R_C$. b) $R_S$ values extracted for various metal contacts. Similar $R_S$ of about 1.8kΩ in average is extracted, independent of the metal used.

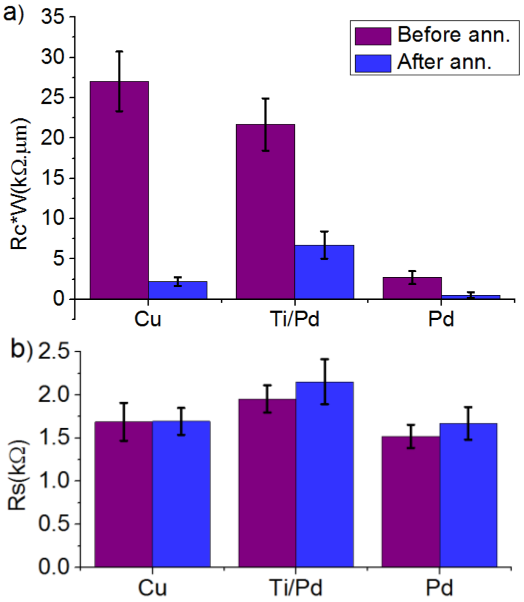

Figure 3. a) $R_C$ values before and after annealing at 300$^{o}$C in Ar for 1 hour. Large improvements were observed after annealing in all cases. b) $R_S$ values before and after annealing at 300$^{o}$C in Ar for 1 hour. Values are similar before and after annealing, indicating that the overall improvement comes from a reduced contact resistance.