EFFECT OF CURRENT STRESSING ON HORIZONTAL CARBON NANOFIBER INTERCONNECTS

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***Abstract*– When a carbon nanofiber (CNF) bridges two gold electrodes, passing high current (current stressing) reduces the total resistance of the system (CNF resistance R_{CNF} and contact resistance R_c) by orders of magnitude. Four-point measurements have revealed that R_c >> R_{CNF}, while current stressing primarily affects R_c. Electrical transport between CNF and Au is studied using a tunneling model in conjunction with current stressing measurement.**

I. INTRODUCTION

Carbon nanostructures are studied as next-generation interconnect materials, due to their apparent immunity to electromigration and excellent electrical and thermal transport properties [1]. Carbon nanofibers (CNFs) have a unique stacked-cup structure, consisting of non-vertical parallel graphene sheets each shaped like a cup. Compared to carbon nanotubes, they can be grown at lower temperature with excellent vertical alignment with respect to the substrate [2], making CNF a promising candidate for future on-chip interconnects.

II. EXPERIMENTS AND MODELING

We present a study on a fundamental interconnect test structure consisting of a carbon nanofiber horizontally bridging two Au electrodes on a SiO_2 substrate. Passing high current (current stressing) reduces the total resistance R_{tot} of CNF and contact resistances (R_{CNF} and R_c) by orders of magnitude. In this article we will show that such decrease in resistance is attributed to change in the interface between the electrode and CNF, where tunneling transport is dominant.

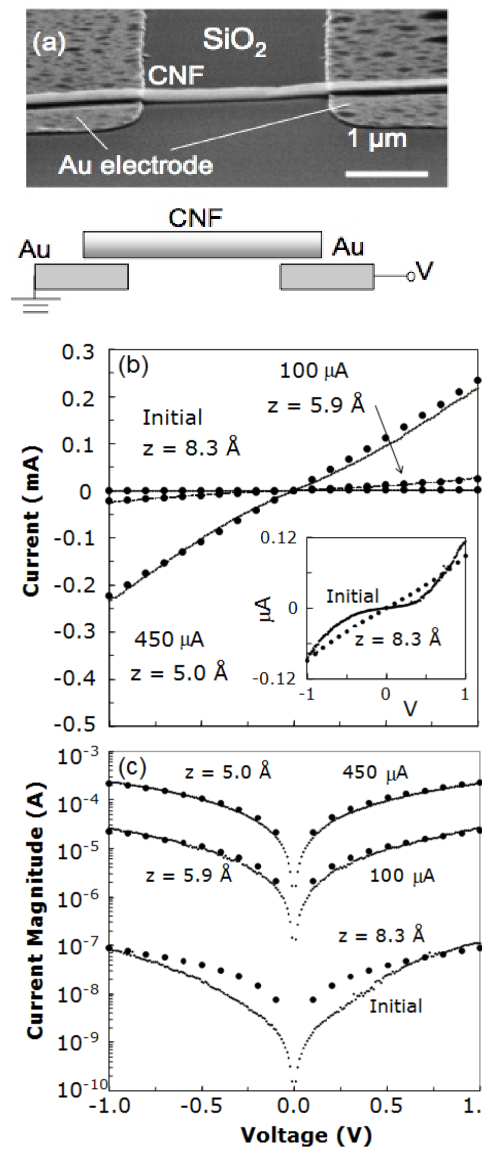

Figure 1. (a) SEM image of a CNF bridging two Au electrodes on SiO_2 substrate. (b) *I-V* behaviors before and after progressive current stressing cycles: the first by 100 µA and the second by 450 µA. Solid circles represent model results. *z*

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values of 8.3, 5.9, and 5.0 Å provide the best fit between experiment and model. (c) Semi-log plot of (b). Nonlinearity reduces with current stressing.

Figure 1(a) shows a scanning electron microscope (SEM) image of a CNF bridging two Au electrodes supported on a SiO_2 substrate. An alcohol solution with CNFs was used to disperse the fibers onto the patterned substrate (drop-cast technique). Figures 1(b) and 1(c) show the current voltage (*I-V*) curves (solid line) before and after current stressing. $R_{tot} = R_c + R_{CNF}$ obtained from $(dI/dV)^{-1}$ at $V = 0$ decreases from MΩ to kΩ range after multiple current stressing cycles. Nonlinearity is clearly reduced as R_{tot} decreases. It becomes critical to determine which contribution is dominant, R_c or R_{CNF}.

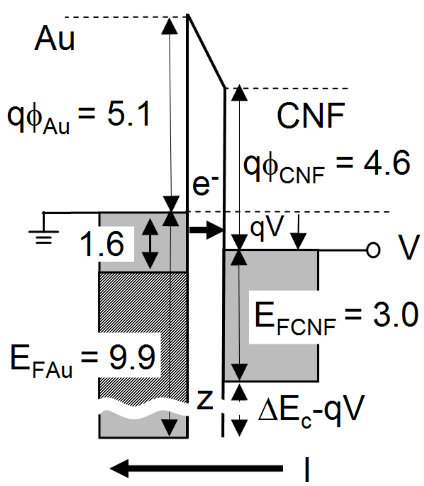

Figure 2. Energy band model for Au-vacuum-CNF tunneling junction with energies in units of eV. CNF is biased at V with respect to Au, and tunneling current I flows from CNF to Au. The dark band in Au is the *d*-band, but within the bias range of $|V| < 1$ V considered here, only the *s*-band is relevant in our model.

To address this problem, we evaluate the resistivity ρ of an unstressed CNF using four–probe measurement, and obtain 4×10^{-5} Ωm, which is comparable to reported results of 4.2×10^{-5} Ωm [3]. Typical R_{CNF} is therefore $\rho L/(\pi r^2) \sim 5$ kΩ, using a CNF length $L = 4$ μm and a radius $r \sim 100$ nm. Thus, $R_c >> R_{CNF}$ and $R_{tot} \sim R_c$ except near breakdown. For further validation of this critical relation, we have fabricated CNF samples with excellent contact, where the CNF is sandwiched between the Au electrode and deposited tungsten [4]. In these W-deposited samples, R_{tot} is already in the kΩ range from the beginning, and stays virtually unchanged even after multiple current stressing cycles.

Based on these two experimental observations, we have concluded that the role of current stressing is to reduce R_c significantly, from the MΩ to kΩ range, while having little effect on R_{CNF}. Because nonlinearity is reduced as R_c decreases, and R_c changes by orders of magnitude, we propose that tunneling transport [5] is responsible for the observed behavior.

Using the energy band scheme shown in Fig. 2 and WKB tunneling formalism [5], *I-V* characteristics are calculated. It is assumed that electron total energy and parallel momentum are conserved throughout the tunneling process. Fermi-Dirac statistics at a finite temperature is incorporated. Tunneling occurs mostly in the energy range between the Au and CNF Fermi levels, which are separated by qV. Because it is possible to estimate the CNF-electrode overlapping area S from SEM images, we have performed modeling calculations using the tunneling gap z as the only unknown parameter. When two tunneling Au-CNF junctions are connected in series with different z values, one junction with larger z will eventually determine the entire *I-V* characteristics because R_c changes by an order of magnitude for $\Delta z = 1$ Å as seen in Fig. 1. Thus, one-junction *I-V* modeling results can be compared with experiments.

Figures 1(b) and 1(c) show modeling results (dots) with measured curves for $S = 0.125$ μm^2 and three z values. The system is dominated by a tunneling junction with $z = 8.3$ Å initially, with 5.9 Å after the first cycle, and with 5.0 Å after the second cycle of current stressing. These calculated results can explain the measurement quite well. It is considered that during current stressing, defects and impurities were annealed out because of Joule heating at the contacts. Thus, the van der Waals attractive force narrowed the Au-CNF interface separation z from

8.3 to 5.0 Å. The calculated separation of 5.0 Å is comparable to the distance between the nanotube and scanning tunneling microscope tip [6] or the distance between the nanotube and gold electrode [7].

III. CONCLUSION

A horizontal CNF interconnect test structure is studied. The effect of current stressing is to reduce the separation *z* at the contacts where tunneling transport occurs, resulting in decrease in R_c and improvement in *I-V* linearity.

ACKNOWLEDGMENT

This work was supported by the United States Army Space and Missile Defense Command (SMDC) and carries Distribution Statement A, approved for public release, distribution unlimited.

REFERENCES

[1] M. Nihei, A. Kawabata, D. Kondo, M. Horibe, S. Sato, and Y. Awano, "Electrical Properties of carbon nanotube bundles for future via interconnects," *Jpn. J. Appl. Phys.,* vol. 44, 1626 (2005).

[2] Q. Ngo, A. M. Cassell, A. J. Austin, J. Li, S. Krishnan, M. Meyyappan, and C. Y. *Yang,* "Characteristics of aligned carbon nanofibers for interconnect Via applications," *IEEE Electron Dev. Lett.,* vol., 27, 221 (2006).

[3] L. Zhang, D. Austin, V. I. Merkulov, A. V. Meleshko, K. L. Klein, M. A. Guillorn, D. H. Lowndes, and M. L. Simpson, "Four-probe charge transport measurements on individual vertically aligned carbon nanofibers," *Appl. Phys. Lett.*, vol. 84 (20), 3972-3974 (2004).

[4] T. Saito, T. Yamada, D. Fabris, H. Kitsuki, P. Wilhite, M. Suzuki, and C. Y. Yang, "Improved contact for thermal and electrical transport in carbon Nanofiber interconnects," *Appl. Phys. Lett.*, vol. 93 (10), 102108 (2008).

[5] C. Duke, *Tunneling in Solids* (Academic, New York, 1969).

[6] T. Yamada, "Modeling of electronic transport in scanning tunneling microscope tip–carbon nanotube systems," *Appl. Phys. Lett*., vol 78 (12), 1739-1741 (2001).

[7] T. Yamada, "Modeling of carbon nanotube Schottky barrier modulation under oxidizing conditions," *Phys. Rev. B*, vol. 69 (12), 125408 (2004).