Electrical Properties of Cu Nanowires

Qiaojian Huang[1], Carmen M. Lilley[1*], Matthias Bode[2], and Ralu S. Divan[2]
[1]Department of Mechanical and Industrial Engineering, University of Illinois at Chicago
3055 Engineering Research Facility, 842 W. Taylor Street, Chicago, IL 60607, USA
[2]Center for Nanoscale Materials, Argonne National Laboratory
9700 S-Cass Ave, Bldg. 440, Argonne, IL 60439, USA
Corresponding email: clilley@uic.edu

***Abstract*-Copper nanowires were patterned with e-beam lithography and fabricated with an e-beam evaporated Cu film. Electrical properties, including resistivity and temperature coefficient of resistance, were characterized for Cu nanowires with a width range of 90 nm to 330 nm. It was experimentally found that the surface and size have apparent influence on the electrical properties. The measured resistivity of the Cu nanowires was found to be size dependent, which was in good agreement with the theoretical models. In addition, smaller values of the temperature coefficient of resistance were experimentally found as the wire width decreases for the Cu nanowires. The size dependent nature of the temperature coefficient of resistance was attributed to the surface and size effects based on the further demonstrative analysis.**

I. INTRODUCTION

Electrical properties of metallic nanowires are of interest to researchers and industry from the point view of the potential applications in the future electronic devices [1-3]. The surface and size effects emerge as dimensions shrinking to the nanoscale. Recent investigations have focused on the surface or size effects on the resistivity, ρ, of copper nanowires[4-8]. Wire resistivity increases when nanowire sizes decrease as a result of surface scattering or grain boundary scattering.

Not only the wire dimensions, but also the temperature has an effect on the resistivity of Cu nanowires. Generally, Joule heating can influence the electrical properties of metallic nanowires and their lifetime to a great extent. Therefore, the accurate measurement of the temperature coefficient of resistance (α_R) is important to study failure. However, to the best of these authors' knowledge, there are limited publications of surface effect on α_R of Cu nanowires.

In this paper, the electrical resistivity (ρ) and temperature coefficient of resistance (α_R) were measured for Cu nanowires. It was found that the surface and size effects have significant influence on ρ and α_R of Cu nanowires. A combined Fuchs-Sondeimer (FS) [9] and Mayadas-Shatzkes (MS) [10] model was used to investigae the surface and size effects on the resistivity. Finally, a finite element method study was carried out to elucidate the cause for size dependent α_R values.

II. EXPERIMENTS

The fabrication process for the Cu nanowires is summarized in Fig. 1. The starting material is a 3-inch silicon substrate with a 300 nm SiN insulator layer deposited by low pressure chemical vapor deposition (LPCVD) in step (a). Two layers of photoresists were spin coated on the substrate to obtain smooth edges for the lift-off process: methyl methacrylate MMA (8.5) methyl acrylic acid (MAA) EL6 (6% in ethyl lactate) in step (b) and PMMA (Poly-methyl methacrylate) in step (c). Electron beam patterning was performed with a Raith150 system in step (d). The sample was developed in MIBK: IPA (methyl isobutyl ketone : isopropyl alcohol = 1 : 3) at room temperature for 30 seconds forming an under cut for the bottom layer of photoresist [11]. A 50 nm thick layer of the Cu film was then e-beam evaporated on the patterned photoresist in step (e). Finally, the unexposed photoresist layers were lifted off with acetone in step (e). The resulting nanowires had length l = 2.04 μm, thickness t = 50 nm, and width w = 90-330 nm.

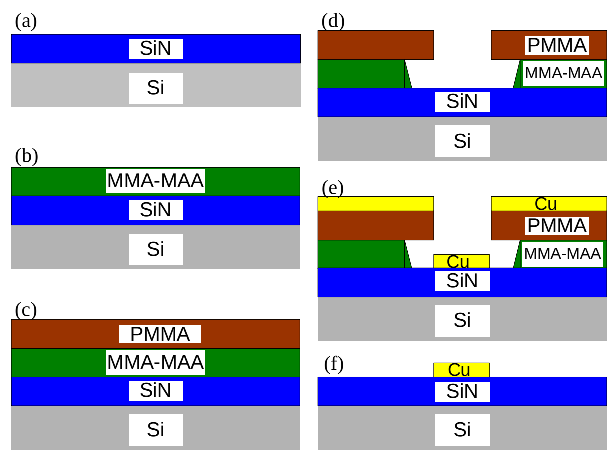

Fig. 1 Micro-fabrication process for Cu nanowires: (a) Deposit an insulator layer of SiN on Si substrate with LPCVD, (b) Spin coat MMA-MAA, (c) Spin coat PMMA, (d) Expose and develop the photoresist (PR), (e) Deposit a Cu film with e-beam evaporation, (f) Lift off the PR.

The fabricated Cu nanowires were characterized with a 4-point probe as shown in Fig. 2(a) to measure the resistivity. Fig. 2(b) is an SEM image for a Cu nanowire with a width of 140 nm. The sample characterizations are performed with a commercial instrument under ultra-high vacuum (UHV) conditions with the chamber pressure lower than 5×10^{-10} Torr. The same system was used to measure the wire length and width. The thickness measurement of the Cu nanowires was performed with an atomic force microscopy (AFM) in non-contact mode.

The temperature dependent resistance of Cu nanowires was determined for a temperature range of 50 K to 297 K. The

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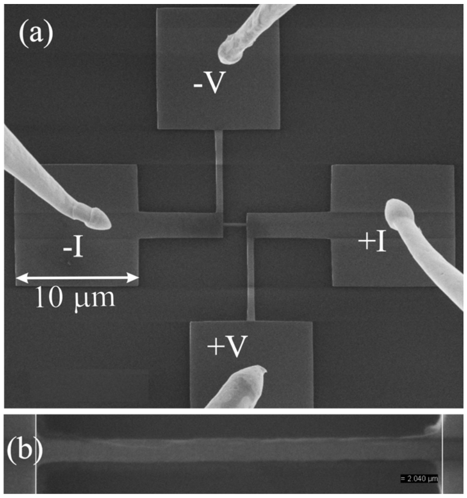

Fig. 2 Sample layout and SEM of a Cu nanowire (l = 2.04 μm, w = 140 nm, and t = 50 nm)

temperature was measured and controlled with by a Lake Shore 331 Temperature Controller with relative temperature accuracy better than 1 K.

III. RESULTS AND DISCUSSION

A. *Surface and size effects on resistivity*

The electrical resistivity for various wire widths was measured to investigate the surface and size effects. Fig. 3 shows the experimental results for the electrical resistivity of Cu nanowires with a length of 2.04 μm and thickness of 50 nm at the room temperature of 297 K. As can be seen, the electrical resistivity increases with decreasing wire width.

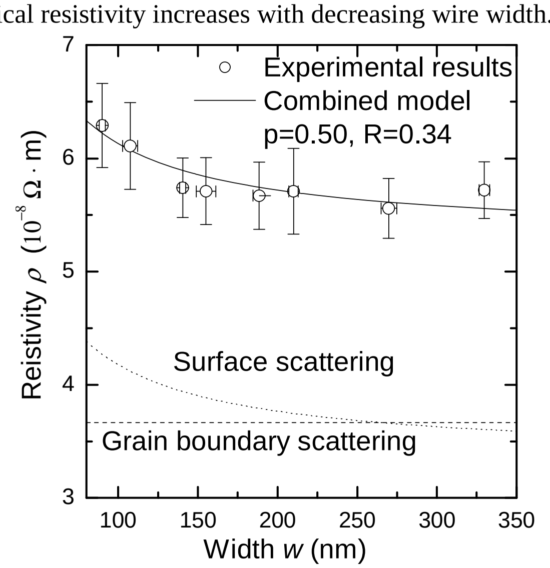

Fig. 3 The experimental resistivity of Cu nanowires as a function of the wire width at room temperature (open circles) compared with the combined model (solid curve), FS model (dotted curve), and MS model (dashed curve). (l = 2.04 μm and t = 50 nm)

Surface scattering has been modeled with the Fuchs-Sondheimer (FS) theory [9, 12] and grain boundary scattering with the Mayadas-Shatzkes (MS) model [10] to study increasing resistivity with decreasing nanowire size. The combined FS-MS model, Eq. (1), was used to fit the experimental data using a least square fitting method [8] where,

$$\rho = \rho_0 \left[2C\lambda_0 (1-p)\left(\frac{1}{t}+\frac{1}{w}\right) + \frac{1}{1-\frac{3\alpha}{2}+3\alpha^2-3\alpha^3 \ln\left(1+\frac{1}{\alpha}\right)} \right] \quad (1)$$

and $\alpha = \frac{\lambda_o}{d}\frac{R}{1-R}$, ρ_o = 1.712 × 10^{-8} Ω-m is the bulk Cu resistivity, C = 1.2 is a constant for a rectangle cross-section [13], λ_o = 40 nm is the electron mean free path [8] at room temperature, and t and w are the thickness and the width of nanowire respectively. The parameter d is the mean grain size, which is estimated to be ~25 nm from SEM imaging. The parameter p is the probability of elastic electron reflection at the surface, where p = 0 for a purely diffuse scattering and p = 1 for a complete elastic reflection. The probability for the electrons to be reflected at the grain boundary is denoted by the reflection coefficient R. With the known parameters, the best fit results for surface scattering and grain boundary scattering coefficients are p = 0.50 and R = 0.34 with a fitting error of 2.5% between the experimental results (open circles) and the theoretical curve (solid curve) in Fig. 3.

It is worth to mention that the fitting coefficients of p and R fall well within the ranges found in literature. Mayandas *et al.* published R = 0.24 for bulk copper [10]. Maitrejean *et al.* found values of p = 0.6 and R = 0.12–0.27 for ionized physical vapor deposited (i-PVD) copper nano lines [5]. Steinhogl *et al.* reported p = 0.2-0.6 and R = 0.50 for electro-chemically deposited copper wires [6].

B. *Surface and size effects on Temperature Coefficient of Resistance*

As a demonstration, Fig. 4 illustrates resistivity, ρ, measurements as a function of temperature for a wire width of 140nm. The closed circles represent the experimental results and the straight line is a least square linear fit with a correlation coefficient of 0.997. From this fit line, the temperature coefficient of resistivity α_ρ for the Cu nanowire is found to be 8.05 × 10^{-11} Ω· m/K, which gives a temperature coefficient of resistance α_R of 1.45×10^{-3} K^{-1} at room temperature. As a comparison, α_R of bulk copper is 4.1×10^{-3} K^{-1} [13] at room temperature.

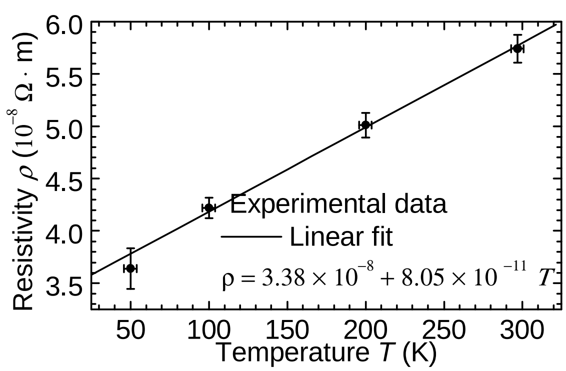

Fig. 4 Temperature dependent resistivity of copper nanowires (l = 2.04 μm, w = 140 nm, and t = 50 nm) with a correlation coefficient of 0.997.

Our experimental results for α_R are similar to Schindler *et al.*[7], who also reported a lower value α_R, 2.5×10^{-3} K^{-1} at 273 K, for Cu nanowires with a width of 44 nm and thickness of 230 nm. The cause for the apparently reduced α_R in Cu nanowires is not well understood. Two possible explanations have been proposed: heating influence from the SEM electron beam or, as suggested by Menke [14] a strain effect caused by the mismatch in the coefficients of thermal expansion α_{TE} for copper (17×10^{-6} K^{-1} at 300 K) [13] and the SiN substrate (4.5×10^{-6} K^{-1} at 300 K) [15]. However, the heating influence from the electron beam is found out to be negligible since the temperature change in the nanowires from electron beam heating is much smaller than the mean temperature of the wires [16]. A mismatch in α_{TE} would indicate that the wires may be significantly strained in either compression or tension. As a result, the strain may affect the resistivity of the wire when cooling from the room temperature of 297 K to 50 K.

We also have measured the temperature dependent resistivity of Cu nanowires for various wire widths (similar to Fig. 4) with the purpose of calculating the corresponding temperature coefficient of resistance, $\alpha_{R.}$ Fig.5 illustrates the temperature coefficient of resistance, α_R, with respect to the wire width of Cu nanowires. As can be seen, the α_R values decrease as decreasing the wire width.

Two factors may contribute to the width dependence of α_R: a size effect from surface diffuse scattering and a mismatch in the thermal expansion coefficients between the wire and its substrate[17-20]. The thermal strain in the nanowire due to a mismatch of the thermal expansion coefficients at the nanowire and substrate interface are suggested to be the same in the samples because the nanowires were tested at the same temperatures range [18]. Therefore, thermal strains are not believed to cause the width dependence of α_R.

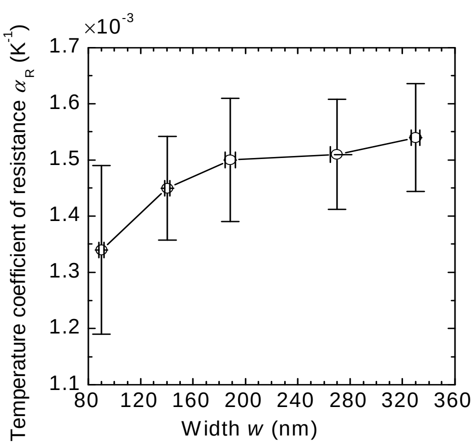

Fig. 5 Temperature coefficient of resistance of Cu nanowires versus the wire width (l = 2.04 μm and t = 50 nm)

It should be noted that the strains on the edges of the nanowires may also partially relax, which will cause an inhomogenous strain distribution in the nanowires. However, this effect would cause increasing α_R values for smaller width wires [17], which is contradictory to the trend we have observed from our experimental results. In addition, a reduced temperature coefficient of resistance has been found in thinner films and has been attributed to surface diffuse scattering [17, 21]. Since the surface area to volume ratio increases as the wire width decreases, increased surface diffuse scattering would decrease the value of α_R for nanowires. Therefore, surface diffuse scattering is believed to cause the width dependence of α_R in our results.

IV. SUMMARY

We have fabricated rectangular Cu nanowires with a width range of 90 - 330 nm and a thickness of 50 nm. Measurements on the electrical properties of these nanowires were performed in a UHV environment. Electrical resistivity was found to increase as the wire width decreases and was found to be a result of surface and size effects. The temperature coefficient of resistance α_R of Cu nanowires was also measured and exhibited size dependent behavior due to surface effects.

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