Thermal coefficient of resistivity of ultrathin Ag films deposited on Cu for applications in emerging interconnect systems

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As the semiconductor industry continues to scale feature sizes, scattering from phonons, surfaces, and grain boundaries results in a significant increase in metal interconnect resistivity. In this work, a thin Ag capping layer is used to modify electron–phonon scattering in 20 nm Cu films to reduce the total resistivity of the bilayer system. To investigate the effect of Ag layer thickness on the electrical properties of the underlying Cu film, the thermal coefficient of resistivity (TCR) is calculated for Cu films that are capped with ultrathin Ag layers of various thicknesses. The TCR exhibited a dependence on the thickness of the ultrathin Ag films deposited on Cu. The slope of the resistance versus temperature is lower for Ag-capped Cu films when compared to bare Cu films. A reduced thermal coefficient of resistivity combined with a lower room temperature resistivity for Ag/Cu films is consistent with a decreased contribution of the temperature dependent portion of the resistivity to the total resistivity, which may prove critical for the viability of future metal-based interconnect architectures. © *2014 American Vacuum Society*. [http://dx.doi.org/10.1116/1.4868718]

I. INTRODUCTION

Multilayered planar metallic films that exhibit variations in various physical properties relative to the thickness of the metal overlayer have been heavily investigated over the past decade. Some of the properties studied include oscillations in the work function of the Ag-on-Fe system,[1] the critical temperature for superconductivity of Pb on Si,[2] and the electron–phonon scattering parameter of the Ag-on-Cu system.[3] A consequence of the observed dependence of electron–phonon scattering on film thickness in the Ag/Cu bilayer system is the possibility of tuning the levels of electron–phonon scattering in the material by finely controlling the thickness of the ultrathin capping layer. Previous studies have shown reductions in the phonon scattering parameter of up to 30%.[3] The goal of this work is to observe if this same reduction can be observed in the case of diffuse electron–phonon scattering in Cu, which contributes significantly to the total resistivity in the metal film at room temperature. The electrical properties of ultrathin Ag capping layers on Cu were studied by measuring their resistive properties with respect to temperature. The thermal coefficient of resistivity (TCR) and the slope of the resistance with respect to temperature were both used as a measure of diffuse electron–phonon scattering. A reduction of the temperature dependent portion of the Cu resistivity is certainly of interest in the semiconductor industry due to the fact that the increase in resistivity in Cu interconnects due to size effects is a persistent challenge to chip manufacturers' progress toward future technology nodes.

II. EXPERIMENTAL CONDITIONS

The substrate was cleaved from a 200 mm, thermally oxidized Si wafer that was cleaned in a solution of 3:1 H_2SO_4:H_2O_2 for 5 min. The wafer was rinsed in deionized (D.I.) water and spin-dried in an N_2 ambient. The films were grown in an ultrahigh vacuum (UHV) system equipped with Ag and Cu Knudsen cells. This allowed the growth of both the Cu and the Ag under UHV conditions. All depositions were done *in situ* at pressures of 10^{-10} Torr. The target thickness of the Cu was 20 nm. The Ag thickness was varied between 5.5 nm and 10 nm.

Film thickness was determined by Rutherford backscattering (RBS). The RBS technique provides an area concentration of atoms in units of atoms per cm^2. This area concentration can be converted to a physical thickness by assuming a mass density (grams per cm^3) of the deposited film.[4,5] For mixed alloys or materials of unknown density, this can cause large errors in thickness between 25% and 100%.[5,6] For homogeneous films of a known material, the bulk elemental density can be used to obtain an accurate thickness if the material is not exceedingly rough or porous.[7] The thickness of thin metal multilayers examined by RBS have shown excellent agreement when compared to TEM cross sectional imaging. Agreement within 1.2 nm has been shown for 5 nm metal multilayer films.[8] The thickness variation was determined by RMS roughness measurements taken by atomic force microscopy.[7,9] Electrical properties of the films were obtained using a four-point sheet resistance measurement. The measurements were done using a Versalab cryostation from Quantum Designs Inc.[10]

For thin films having a thickness equal to or less than half the spacing of the four probes, and for films with an area greater than the probe spacing by ten times or more, it is valid to equate the sheet resistance to

$$R_s = \frac{\pi}{\ln 2}\frac{V}{I}, \tag{1}$$

where V is the voltage measured between the two inner probes and I is the current applied to the two outer probes.[11]

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From the sheet resistance, the resistivity can be calculated within the error of the thickness measurement by

$$\rho = R_s t, \tag{2}$$

where t is the thickness of the film. To account for variations in the thickness, the RMS roughness values in Table I were taken as the thickness maxima and used to calculate an average thickness error of about 10%. The thickness error is included in the resistivity calculations. When calculating the total resistance of a bilayer metal film, the following is valid for the system:

$$\frac{1}{R_{s_{\mathrm{Ag/Cu}}}} = \frac{1}{R_{s\mathrm{Ag}}} + \frac{1}{R_{s_{\mathrm{Cu}}}}, \tag{3}$$

where $R_{s\mathrm{Ag/Cu}}$ is the total sheet resistance of the Ag/Cu film, $R_{s\mathrm{Ag}}$ is the sheet resistance of the Ag layer, and $R_{s\mathrm{Cu}}$ is the sheet resistance of the pure Cu layer. Equations (1) and (3) can be combined to find the effective resistivity of the individual films. To measure the resistance, I–V sweeps were performed. The applied current was swept from −10 to 10 μA. To ensure that significant joule heating was not taking place, I–V sweeps were done prior with currents up to 5 milliamps, and no change in resistive characteristics were observed. The electrical data were recorded for each of the Ag/Cu films at several temperatures between 50 K and 300 K. With this data, the TCR could be calculated by

$$TCR = \frac{1}{R_{S(300K)}} \frac{dR}{dT}, \tag{4}$$

where $R_{s(300\,\mathrm{K})}$ is the resistance of the film measured at 300 K. dR/dT is the slope of the measured resistance versus temperature.

III. RESULTS

The resistivity of the bare 20 nm Cu film as-deposited at room temperature was 8.3 $\mu\Omega$ cm. This is significantly higher than the typical bulk values reported to be about 1.7–1.8 $\mu\Omega$ cm. This is expected due to dimensional constraints. As the dimensions of the Cu film decrease, there are increased contributions from surface and grain boundary scattering at dimensions less than 100 nm.[12] Commonly in microelectronics, as-deposited Cu films are annealed at about one-third the melting temperature of Cu, which is known to cause recrystallization in the film and increase the size of the Cu grains, leading to a decrease in the resistivity of the films.[13]

TABLE I. Calculated room temperature resistivity of Ag/Cu films. Ag/Cu films exhibit lower resistivity than pure Cu films.

Ag thickness	Resistivity$_{300\,\mathrm{K}}$ ($\mu\Omega$ cm)	Resistivity$_{60\,\mathrm{K}}$ ($\mu\Omega$ cm)	Error (+/− nm)
0 nm Ag (pure Cu)	8.3+/−0.05	4.9	0.05
5.5 nm	2.9+/−0.5	1.5	0.5
6.5 nm	3.4+/−0.5	2.4	0.5
8.0 nm	3.8+/−0.5	2.5	0.5
10 nm	4.5+/−0.6	2.8	0.6

TABLE II. RMS roughness values are shown for Ag/Cu films.

Ag thickness	RMS (nm)
0 nm Ag (pure Cu)	1.0
5.5 nm	1.6
6.5 nm	1.9
8.0 nm	1.9
10 nm	2.5

The resistivity of the as-deposited Cu film is comparable to nonannealed, as-deposited films of similar dimensions reported elsewhere.[14] The resistivities of the Ag/Cu samples are displayed in Table II. The resistivities of the as-deposited Ag/Cu films were consistently lower than the as-deposited Cu films. The resistivities of the Ag/Cu films were 2.9, 3.4, 3.8, and 4.5 $\mu\Omega$ cm for, respectively, 5.5, 6.5, 8.0, and 10 nm-thick Ag films. It has been previously reported that as-deposited Ag/Cu films exhibit larger grains than as-deposited Cu films.[15] The Ag/Cu films show increasing resistivity as the Ag thickness increases. RMS roughness acquired by atomic force microscopy shows that roughness is increasing as the film thickness increases (Table II).

The equation for the TCR in Eq. (4) is comprised of the linear slope of the resistance with respect to temperature, dR/dT, and the resistance at 300 K, $R_{s(300\ \mathrm{K})}$. The slopes of the resistance versus temperature curves in Fig. 1 were used to obtain dR/dT. Using the dR/dT values along with R_s (300 K) values in Table III and after applying Eq. (4), values for TCR were obtained. As shown in Fig. 2, the TCRs of the films were 1.7×10^{-3} K^{-1} for 20 nm bare Cu films, and 1.93×10^{-3} K^{-1}, 1.42×10^{-3} K^{-1}, 1.47×10^{-3} K^{-1}, and 1.73×10^{-3} K^{-1} for, respectively, 5.5, 6.5, 8.0, and 10 nm-thick Ag layer.

There was a 30% difference in the TCR between the samples with a 5.5 nm and 6.5 nm-thick Ag layer. The TCRs of

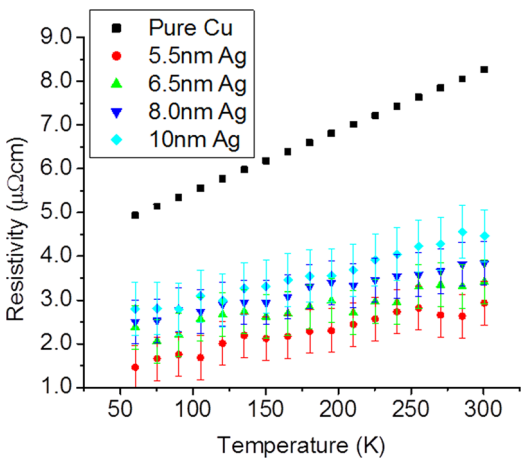

FIG. 1. (Color online) Resistivity vs temperature calculated from thickness and sheet resistance measurements for Ag/Cu films.

TABLE III. Room temperature resistance measurement, $R_{0(300\ K)}$, sheet resistance, $R_{s(300\ K)}$, slope of resistance vs temperature, dR/dT, and thermal coefficient of resistivity of Ag films grown on Cu.

Sample	$R_{S\ (300\ K)}$ (Ω)	dR/dT (Ω*K^{-1})	TCR (K^{-1})
Pure Cu (20 nm)	4.13272	6.93×10^{-3}	1.68×10^{-3}
5.5 Ag overlayer	1.15089	2.22×10^{-3}	1.93×10^{-3}
6.5 nm Ag overlayer	1.28607	1.83×10^{-3}	1.42×10^{-3}
8.0 nm Ag overlayer	1.37282	2.01×10^{-3}	1.47×10^{-3}
10 nm Ag overlayer	1.49037	2.58×10^{-3}	1.73×10^{-3}

the films with the added Ag capping layers oscillate around the baseline value of the bare Cu film as a function of thickness. The normalized TCR values are plotted with respect to the Ag layer thickness in Fig. 3. The data show that there was a decline in the TCR at about 6.5 nm of Ag followed by a gradual increase and eventual overshoot above the TCR of the underlying Cu film for a 10 nm-thick Ag layer. The correlation is similar to what has been observed for the electron–phonon scattering parameter for thin films of Ag deposited on Cu. In the literature, these oscillations were attributed to quantum well state transitions that occur at critical Ag thicknesses and a minimum in the electron-phonon scattering parameter was observed at about 23 ML of Ag deposited on Cu.[3] The thickness in Ref. 3 is comparable to the thickness at which a minimum was seen in the films' TCR in this study.

IV. DISCUSSION

Table I shows the values of the resistivity measured at 60 K and the resistivity measured at 300 K. The resistivity of the pure Cu film increased from 4.94 to 8.27 μΩ cm, corresponding to a net rise of 3.3 μΩ cm. The Cu films with a thin Ag capping layers exhibited a resistivity increase only between 1.0 and 1.7 μΩ cm. This evidence suggests that the temperature dependent scattering processes in the Ag/Cu films are fewer than those in the bare Cu film. This is consistent

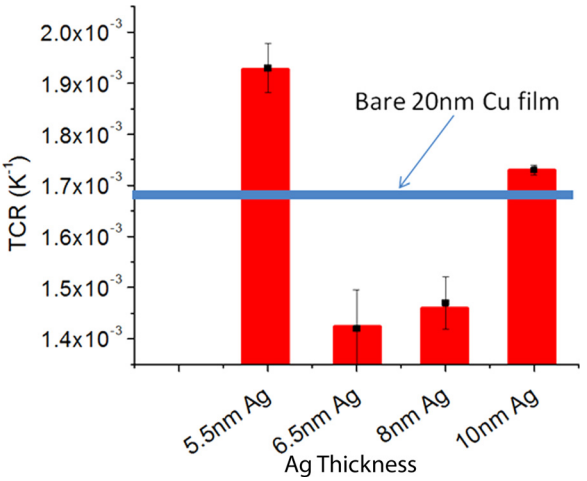

FIG. 2. (Color online) TCR of Ag/Cu films. TCRs were calculated to be 1.7 × 10^{-3} K^{-1} for 20 nm bare Cu films, and 1.93 × 10^{-3} K^{-1}, 1.42 × 10^{-3} K^{-1}, 1.47 × 10^{-3} K^{-1}, and 1.73 × 10^{-3} K^{-1} for 5.5, 6.5, 8.0, and 10 nm thick Ag layers, respectively.

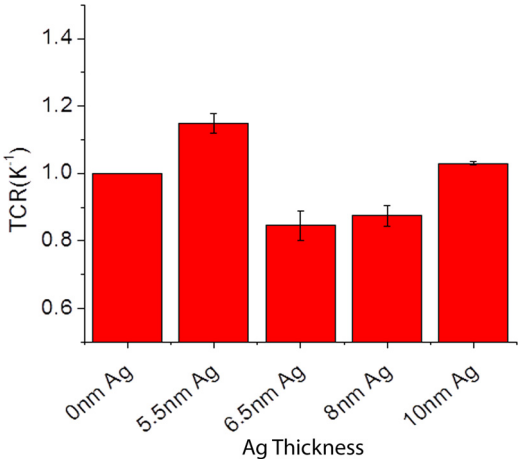

FIG. 3. (Color online) TCR of Ag/Cu films normalized to the TCR values of the pure Cu samples (labeled "0 nm Ag"). The data show that there is a decrease in the TCR with a minimum at 6.5 nm followed by a gradual increase and eventual overshoot above the TCR of the underlying Cu film at a Ag thickness of 10 nm.

with prior reports in the literature, and which suggested that quantum oscillations in the phonon scattering parameter occur at critical Ag thicknesses on Cu. The oscillatory behavior was attributed to the quantum well resonances between the Ag overlayer and the underlying Cu film transitioning to quantum well states at specific Ag thicknesses.[3,16,17] The oscillation of the thermal coefficient resistivity of the Ag/Cu films is consistent with what has been reported.

V. CONCLUSIONS

Oscillations in the thermal coefficient of resistivity were observed for Ag films of various thicknesses deposited on Cu. Films were deposited by molecular beam epitaxy. A drop in the thermal coefficient of resistivity could be observed just above a Ag thickness of 5.5 nm followed by a gradual increase as the Ag thickness increased. The apparent reduction in the TCR for the Ag/Cu samples at certain Ag thicknesses indicates that it is indeed possible to manipulate the temperature dependent component of this system's total resistivity using ultra-thin planar metallic capping layers on Cu. In the future, it will be beneficial to study the electrical behavior of lithographically patterned Ag-capped Cu lines representative of common interconnect structures that are typically found in a microelectronic system.

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