Low-frequency Noise and Defects in Copper and Ruthenium Resistors

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Abstract

1.8-MeV proton irradiation to a fluence of 10^{14}/cm^2 does not significantly affect the resistance or low-frequency noise of copper or ruthenium resistors fabricated via modern microelectronic fabrication techniques used to form metal lines. The room-temperature noise of these Cu and Ru resistors is surprisingly similar to that of Cu and Pt metal lines and wires fabricated using late-1970s nano-fabrication techniques; however, measurements of the temperature dependence of the noise show that the defect kinetics are quite different among the various materials. A large increase in noise magnitude observed above 200 K in Cu but not Ru is consistent with the superior resistance to electromigration that Ru lines have shown, relative to Cu.

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As interconnect lines are scaled to smaller dimensions, copper is less favorable as a base metal due to increasing line resistivity and decreasing electromigration (EM) reliability.[1-4] Platinum-group metals such as ruthenium are candidates to replace Cu in future nodes because they have (1) low bulk resistivity, (2) small carrier mean-free paths, of particular importance at narrow dimensions, and (3) higher melting points, which often correlate with longer EM lifetimes.[1,2,4,5] Ruthenium is particularly promising because of its compatibility with CMOS technology,[6,7] favorable area-dependence of resistivity,[5] and higher fusing-current densities and EM lifetimes relative to Cu.[5,7,8] Thus, the comparative performances and reliability of Ru and Cu metallization are of high interest.[9] Their radiation responses are also of significance for potential use in space or particle-accelerator applications.

Low-frequency ($1/f$) noise has been shown to be helpful in characterizing reliability-limiting defects and impurities in microelectronic materials and devices.[10-17] $1/f$ noise measurements can be an early indicator of EM damage,[11-14,17] and/or provide insight into the nature and effective-energy distributions of reliability-limiting defects and impurities in as-processed and irradiated materials and devices.[10-14,16-18] In this Letter, we show that the room-temperature $1/f$ noise magnitudes of Ru and Cu resistors do not change significantly after high-fluence proton irradiation. We find surprisingly similar results for the room-temperature noise of these Ru and Cu resistors, fabricated via state-of-the-art microelectronics fabrication techniques used to form metal lines, and Pt and Cu wires and films fabricated more than 35 years ago using first-generation Ar^+-sputtering-based nano-lithographic and/or mechanical scribing techniques.[19-21] We also find that the temperature dependence of the low-frequency noise of Ru and Cu resistors is described well by the Dutta-Horn model of $1/f$ noise.[18] Qualitatively different effective defect-energy distributions are observed for Ru and Cu. The nature of the defects and/or impurities responsible for the noise and potential links to EM reliability are discussed.

The Cu lines evaluated in this work are fabricated by a damascene metallization process consisting of (1) 3 nm plasma-vapor-deposited (PVD)-TaN/Ta, with a PVD-Cu seed and (2) Cu electrochemical plating and chemical-mechanical polishing in 30 nm wide trenches. These trenches are formed in chemically vapor-deposited SiOCH low-k dielectric (dielectric constant $k = 3.2$) via double lithography-etch patterning. Lines are capped by 30 nm thick SiCN.[22] Ru lines were fabricated using a spacer-assisted double-patterning technique.[6] Trenches are formed using a Si_3N_4 spacer, deposited onto a SiO_2 core and etched anisotropically so the spacer remains on the core sidewalls. One of the spacers is removed to form a single metal line. After wet-etching the spacer using hot phosphoric acid, Ru is atomic-layer deposited in the trenches with a liner of 0.3 nm TiO_2. The Ru lines are 18 nm wide.[6]

Low-frequency noise measurements were performed at temperatures from 90 to 400 K with a system based on a Hewlett-Packard 4140 voltage source, Janis cryostat and Cryocon34 temperature controller, and Stanford Research SR 560 pre-amplifier and SR 760 spectrum analyzer.[23] At least two devices were tested for each set of conditions in this study, with results varying by less than ± 20%. Some devices were irradiated with all terminals grounded with 1.8 MeV protons (range ~ 20 μm in Si) to a fluence of $10^{14}/cm^2$ at a flux of 2×10^{13} protons/h using the Vanderbilt Pelletron.[24]

Figure 1 compares room-temperature noise magnitudes S_V of (a) Ru and (b) Cu resistors as a function of frequency f and applied voltage V for as-processed and proton-irradiated devices. Values of S_V are proportional to $1/f^{\alpha}$, with $\alpha = 1.10 \pm 0.05$ for Ru, and $\alpha = 1.05 \pm 0.05$ for Cu. In each case S_V increases as ~ V^2, consistent with ohmic response.[10,16,18] No significant changes are observed in S_V or resistance due to proton irradiation. The combination of proton fluence and energy in Fig. 1 (10^{14}/cm^2, 1.8 MeV protons) can generate displacement damage at levels comparable to or greater than observed in realistic space[24,25] or high-luminosity particle accelerator environments.[26] Such high proton fluences typically lead to large changes in the noise of semiconductor/insulator-based devices.[16] This emphasizes the effectiveness of damage-recovery processes at room temperature in these metal resistors, and absence of significant influences of surrounding layers[1-8,17,22] on the noise. The results of Fig. 1 are consistent with those of Pelz and Clarke,[27,28] who observed increases in noise of 500-keV electron-irradiated Cu films at 90 K, and full recovery upon warming to room temperature, and of Garamew, et al.,[29] who find negligible changes in the current-voltage characteristics and low-frequency noise of metallic TaS$_2$ charge-density-wave devices upon irradiation to similar proton fluence.

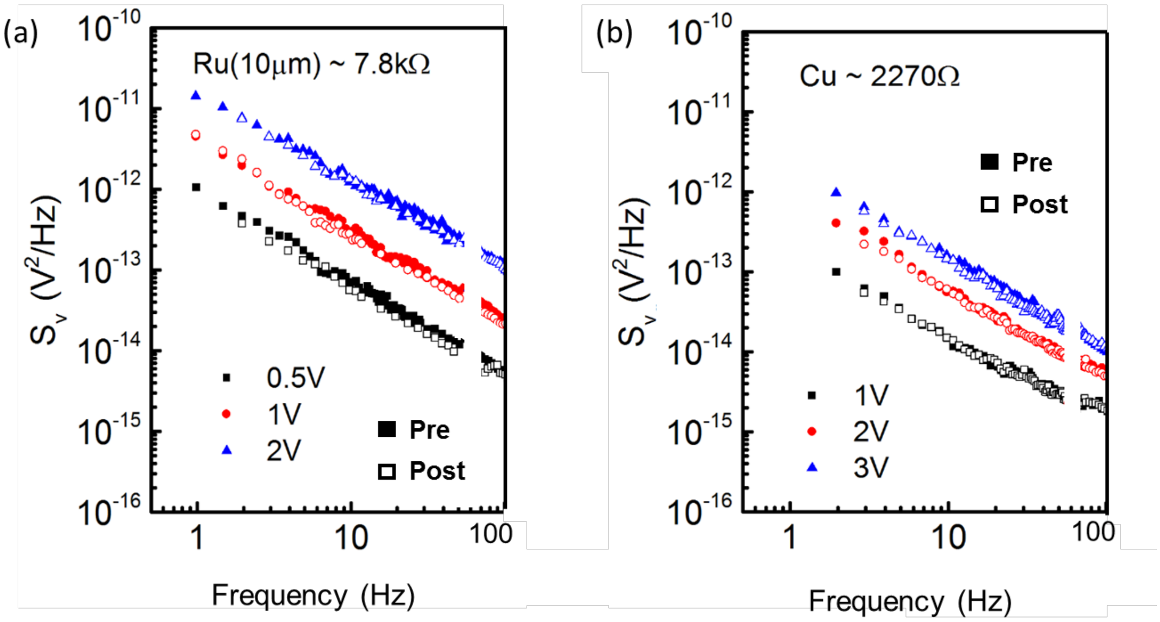

FIG. 1. Excess voltage-noise power-spectral density S_v measured at 295 K vs. applied voltage for (a) Ru resistors of length L = 10 μm and cross-sectional area σ ~ 200 nm^2, and (b) Cu resistors with L = 150 μm and σ ~ 2800 nm^2. Solid symbols denote as-processed devices; open symbols denote devices irradiated at 295 K with 1.8 MeV protons to a fluence of 10^{14}/cm^2 with all terminals grounded. No significant changes in the noise or resistance are observed. Thermal and amplifier noise are substracted to obtain S_v, and spikes in noise spectra due to 60 Hz pickup are removed for clarity.

Figure 2 compares room-temperature voltage- and frequency-normalized noise magnitudes $S_V f/V^2$ of the Ru and Cu resistors of this work with results of previous studies of Pt and Cu wires and films performed more than 35 years ago.[19-21] Wires in those studies were fabricated (inset of Fig. 2) by (a) deposition of a metal mask onto a glass slide, (b) Ar$^+$ ion milling to form small steps, (c) removal of the mask, (d) sputter-deposition of Pt at normal incidence, (e) Ar$^+$ ion milling at an angle to remove all of the Pt except that remaining in the shadow of the step.[19] The wires formed by this process were contacted with silver paint. Continuous Pt wires formed via this method had cross sections as small as ~ 200 nm^2,[19,20] comparable to the Ru resistors of this study. Thin-film Pt and Cu resistors were scribed using a mechanical manipulator with a sharp probe tip in these earlier studies.[20,21]

Figure 2 shows that the normalized noise magnitude at f = 10 Hz follows approximately the 1/N dependence expected from the empirical relation: $S_V = \alpha_H V^2/Nf$. Here α_H is the dimensionless Hooge parameter and N is the number of atoms in the resistor, which for metals is approximately equal to the number of carriers.[10,16,18,30,31] The ~ 1/N scaling and absence of dependence on surface-to-volume ratio are evidence of the bulk origin of the noise.[20,30,32] Despite the significant differences in the sophistication of processing techniques, the room-temperature noise of the Ru films in this study is comparable to or only slightly less than the noise of the quietest Pt wires fabricated via step-edge lithography.[19,20] The room-temperature noise of the Cu films here is comparable to that of the quieter Cu films patterned by scribing.[21] Given that the noise of metal films is known to be quite sensitive to defects and impurities,[10,16,18,27,28,33-35] this result is surprising, and strongly suggests that only a small subset of the defects and impurities in the samples contribute to the noise of these devices under these measurement conditions. Thus, the kinetics of the underlying fluctuation phenomena are also of great interest.

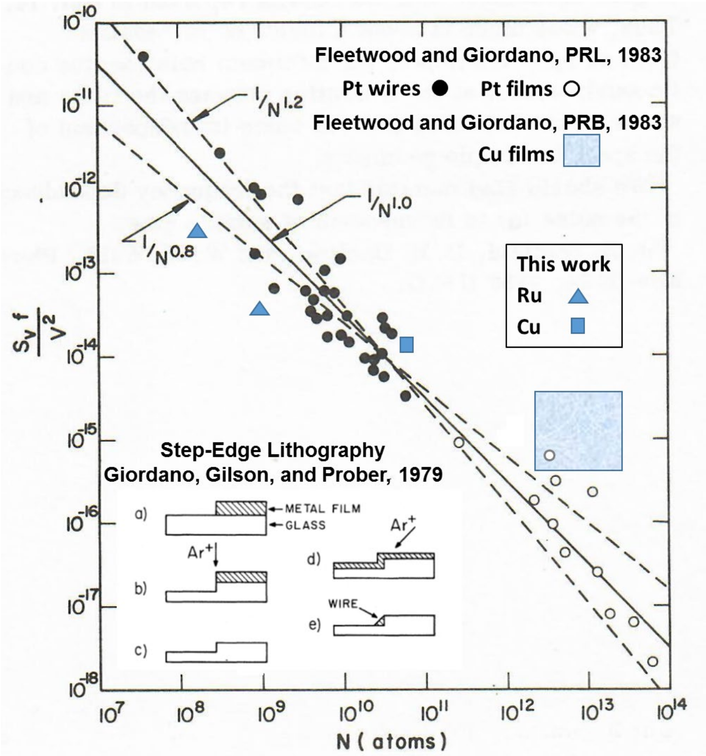

FIG. 2. Normalized noise magnitudes at 295 K and f = 10 Hz for (1) as-processed Ru (L = 10 μm and L = 50 μm; triangles) and (2) Cu resistors of this work (small, solid box), compared to literature results for (3) Ar$^+$-sputtered Pt wires fabricated using "step-edge" lithography (solid circles) and (4) Ar$^+$-sputtered Pt films (open circles) and (5) thermally evaporated Cu films (large, shaded box) scribed to final dimensions using a mechanical manipulator and sharp probe tip. Lines are aids to the eye with slopes $1/N^{1.0 \pm 0.2}$. The lithography diagram is from Giordano, et al., 1979 (Ref. 19); Pt noise measurements are from Fleetwood and Giordano, 1983 (Ref. 20); measurements of thermally-evaporated and scribed Cu films (large, shaded box) are from Fleetwood and Giordano, 1983 (Ref. 21). Symbol sizes and boxes are similar to, or greater than, variations and/or uncertainties in sample dimensions and noise magnitudes.

Dutta and Horn have shown that, if (1) the noise is caused by a random thermally-activated process having a broad distribution of energies $D(E)$ relative to kT, where k is the Boltzmann constant and T is the temperature, (2) the fluctuation process is characterized by an attempt frequency f_o much higher than the measuring frequency, and (3) the coupling constants between the random processes responsible for the noise and the total integrated noise magnitude are independent of frequency, the frequency and temperature dependences of the noise are coupled via:[10,18,36]

$$\alpha(\omega, T) = 1 - \frac{1}{\ln(\omega\tau_0)}\left(\frac{\partial \ln S_V(T)}{\partial \ln T} - 1\right). \tag{1}$$

Here $\tau_o = 1/f_o$ is the characteristic attempt time of the process leading to the noise, and $\omega = 2\pi f$. Significant deviations from Eq. (1) can occur, for example, in metal films for which magnetic interactions dominate over defect scattering (e.g., Ni, Cr),[37-39] and cases for which defect annealing or new defect creation occur during the noise measurement sequences.[40] For noise that satisfies Eq. (1), as often observed in practice,[18] one can infer the shape of the effective defect-energy distribution $D(E_o)$ from noise measurements versus temperature via:

$$D(E_0) \propto \frac{\omega}{kT} S_V(\omega, T) \tag{2}$$

where the defect energy is related to the temperature and frequency through the simple expression:[12]

$$E_o \approx -kT\ln(\omega\tau_o)\,. \tag{3}$$

If, in the simplest case, the noise results from thermally-activated processes with two energy levels, E_o is the barrier that the system must overcome to move from one configurational state to another.[10,16,18] For cases in which Eq. (1) is applicable, plots of $S_v f/T$ versus temperature essentially map out effective defect-energy distributions for materials or devices of interest.[10,16,18]

Figure 3 compares the temperature dependences of the quantity $S_v Nf/T$ for the Ru and Cu resistors of this study, fabricated via state-of-the-art microelectronics fabrication techniques, and Pt wires fabricated more than 35 years ago using step-edge nano-lithography.[20,41,42] This normalization is consistent with the N, f, and T dependences of Fig. 2 and Eq. (2), thereby facilitating relative comparisons of effective defect-energy distributions. Equation (1) applies at least approximately for all devices (insets of Fig. 3, for example).[10,16,18,33,41,42] For values of T below ~190 K, $S_v Nf/T$ is significantly larger for Ru resistors than for Cu resistors or Pt wires. For 190 K $\leq T \leq$ 280 K, values of $S_v Nf/T$ for Cu resistors increase significantly; values of $S_v Nf/T$ for Pt wires and Ru resistors are similar in magnitude and relatively constant with temperature. At higher temperatures, $S_v Nf/T$ increases dramatically for Pt wires, moderates and plateaus for Cu resistors, and remains approximately constant for Ru resistors. Similar results were obtained on at least four devices of each type. Hence, the results of Fig. 3 strongly suggest that the defects and/or impurities primarily contributing to the noise of Ru resistors have lower effective energies than those primarily contributing to the noise of the Cu resistors and Pt wires.

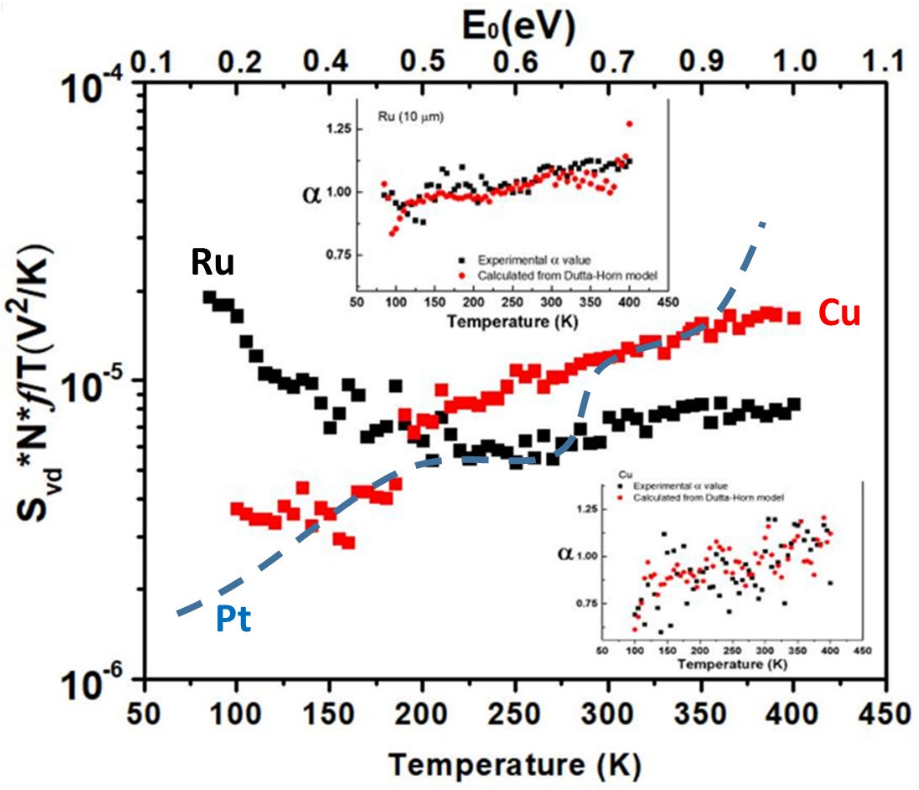

FIG. 3. Excess, normalized voltage noise-power spectral density S_vNf/T measured at $f = 10$ Hz and 1 V bias as a function of T in 5 K intervals for an as-processed Ru resistor of length $L = 10$ μm and cross-sectional area $\sigma \sim 200$ nm^2 (black squares) and as-processed Cu resistor with $L = 150$ μm and $\sigma \sim 2800$ nm^2 (red squares). Results for a "low-noise" Ar$^+$-sputtered Pt wire also are shown, normalized to 1 V (dashed curve, after Fleetwood, et al., 1987, Ref. 41). The upper x-axis is the effective defect-energy scale derived from Eq. (2), assuming $\tau_o \approx 10^{-14}$ s. The Dutta-Horn model is found to be approximately valid for the Ru (upper inset) and Cu (lower inset) resistors via measurements and calculations using Eq. (1), as also confirmed for Pt wires in Ref. 42.

Experimental and theoretical studies by Pelz et al. on Cu[28], Zimmerman et al. on Pd,[43] and Liang et al. on black phosphorus based MOS structures[32] demonstrate that motions of simple point defects, e.g., vacancies and interstitials, and/or atomic hydrogen can lead to low-frequency noise in metals and semiconductor devices at temperatures below ~ 200 K. These types of processes most likely account for the enhanced noise magnitudes of Ru resistors at low temperatures in Fig. 4. Fluctuations in resistance associated with these phenomena occur too rapidly to lead to observable $1/f$ noise at higher values of T. Studies by Pelz et al.,[28] Holweg et al.,[44] and Ralls, et al.[45] further show that rotational motions of complex defect clusters within the films can account for the low-frequency noise observed at higher temperatures.[28,44,45] These complex defect motions most likely lead to the enhancement of noise magnitudes observed in Fig. 3 for Cu films above ~200 K and Pt wires above ~280 K. Stable, electrically detectable defect clusters are difficult to create in metals at room temperature or above via irradiation at electron or proton fluences relevant to space[46] or particle-accelerator applications,[47] consistent with the results of Fig. 1 and of Pelz, et al.[27,28] and Garamew, et al.[29] The increased noise in Pt wires at higher temperatures is most likely due to sputtering-induced defects and Ar impurities.[33,41,42]

Previous work by Eberhard, Dutta, and Horn[48] on metal films and Beyne et al.[17] on resistors nominally identical to ones measured in this work show a peak in the noise of Cu at temperatures between ~ 400 K and ~ 500 K. This noise peak has been associated by Beyne et al.[17] with the activation of a diffusion mechanism that plays a significant role during EM degradation of Cu lines. The barrier, liner, capping, and dopant materials are found to affect EM degradation and noise kinetics similarly,[49,50] consistent with a bulk origin for the noise. In all of these examples, the noise of Cu follows Dutta-Horn kinetics,[17,48-50] as commonly observed for microelectronic materials and devices.[16] Complex defect motions like those responsible for the higher-temperature increase in Cu noise have been shown to serve as precursors to EM phenomena in Cu lines.[17,51] The absence of this increased noise in Ru is therefore consistent with the greater resistance of Ru lines to electromigration than Cu lines.[7,8,52]

In conclusion, we have found that high-fluence proton irradiation does not significantly affect the resistance or low-frequency noise of Cu or Ru resistors. Room-temperature noise magnitudes of Cu and Ru resistors fabricated via state-of-the-art microelectronic fabrication techniques used to form metal lines are quite similar to those of Cu and Pt thin metal films and wires in previous studies that were fabricated by much less sophisticated techniques;[19-21] however, the defect kinetics are quite different among the various materials. The association between the low frequency noise and the onset of electromigration in Cu lines suggests that complex defect rotations are a precursor to EM-induced degradation in these structures. The large increase in noise magnitude above 200 K that occurs in Cu but not in Ru is consistent with the enhanced resistance of Ru lines to electromigration, as compared with Cu.[7,8,52]

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