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Resistivity of epitaxial copper nanolines with trapezoidal cross-section

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ABSTRACT

The resistivity of epitaxial Cu nanolines with line width ranging from 20 to 180 nm and line height from 40 to 50 nm was measured using a four-point probe technique. The Cu nanolines were fabricated using ebeam lithography with a polymethyl methacrylate bilayer resist system for improved line edge smoothness. The cross-section profile of the lines was examined using the focused ion beam milling technique. The results indicate that the cross-section should be more accurately described as trapezoidal rather than as rectangular. Using the trapezoidal profile, the electrical resistivity was calculated from the measured resistance data. Modeling based on the Fuchs–Sondheimer (FS) theory using the trapezoidal profile was also carried out. The results were compared with the experimentally calculated resistivity data. For Cu lines with line width less than 30 nm, the measured resistivity was shown to be up to 20% higher than the value predicted by the FS theory. Further examination of Cu lines using atomic force microscopy and scanning electron microscopy was conducted to extract the surface roughness and line edge roughness information. Their contribution to the resistivity increase was estimated to be only up to 3% for the Cu nanolines fabricated, which did not significantly contribute to the overall resistivity for Cu lines with line width less than 30 nm. Other possible factors affecting the resistivity of the Cu nanolines were also discussed, including the oxide formation on the surface of the Cu lines.

1. Introduction

Dimension shrinkage of Cu interconnects leads to the increase of size-dependent electrical resistivity [1–3]. It becomes significant when the dimensions approach and are smaller than the mean free path of Cu at 39 nm [2]. Various factors contribute to the total resistivity of Cu nanowires, including electron–phonon scattering, grain boundary scattering, surface scattering, and defect and impurity scattering [2–4]. The Bloch–Gruneisen model [5] is used to describe the electron–phonon scattering, the Mayadas–Shatzkes (MS) model [6] accounts for the grain boundary scattering, and Fuchs–Sondheimer (FS) theory [7,8] is used for surface scattering modeling. For epitaxially grown Cu nanolines, the grain boundary scattering can be neglected due to the elimination of the grain boundaries in the metal [9]. Thus the resistivity increase caused by the size-effect is expected mainly due to the surface scattering.

Extensive studies have been reported on the size-dependent electrical resistivity of metal nanolines with a rectangular cross-section. So far very few studies have reported works based on a trapezoidal cross-section profile. On the other hand, for various realistic situations, the trapezoidal profile is more accurate to describe the cross-section of metal lines prepared with common fabrication processes, such as electroplating, and ebeam writing [10–12]. Travaly et al. [11] concluded that the approximation of a 160 nm metal pitch trapezoidal cross-section as rectangular shape may lead to an ~6% overestimation of cross-sectional area. As the dimensions of the nanolines diminish further, the difference will be more significant. In this case, the solution for a trapezoidal cross-section profile provides more accurate resistivity estimation for a metal line than the rectangular approximation.

Other factors that affect the resistivity of metal nanowires at the deep nanometer range are the surface roughness and line edge roughness (LER) [4,12–16]. The surface roughness and LER are usually introduced by the polymer and metal patterning and deposition processes, including photoresist lithography, etching, and metal deposition. From a pure geometrical point of view, the surface roughness and LER can result in random broadening and narrowing of the cross-sectional area along the metal nanolines. Steinhogl et al. [13] pointed out that the LER can increase the actual effective resistivity (by a factor of 4/3) compared to a line with smooth line edge. Purswani et al. [14] indicated that a 5 nm amplitude surface roughness on a 20 nm thick metal layer can result in a 40% increase of the resistivity. Furthermore, as pointed out by Steinhogl et al. [13], when taking into account the size-effects on these nanolines, the resistivity contribution of narrower portions is probably larger. As a result, the effective resistivity will be higher due to the size-dependent surface scattering. So far, most related studies were focused on artificial LERs or simulations only, due to the difficulty of obtaining accurate, three dimensional information of real nanolines. Ercius et al. [12] employed an electron tomography 3D reconstruction

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strategy to tackle the cross-section measurement problem. However, it has limited applications due to the instrumental availability.

In this paper, we report the fabrication of epitaxial Cu nanolines. We employed an ebeam lithography method with a polymethyl methacrylate (PMMA) bilayer resist system for Cu line preparation, which significantly improved the line edge smoothness. The focused ion beam (FIB) milling technique was used to examine the cross-sectional profile of the lines. The goal is to provide more accurate information on the line cross-section profile, and its effects on the estimation of the total electrical resistivity for Cu lines with dimensions below the mean free path regime. We further examined the surface roughness and LER using atomic force microscopy (AFM) and scanning electron microscopy (SEM). Their contributions to the total resistivity increase were evaluated as well. Finally, other factors affecting the resistivity, including the oxide formation on the surface, were also discussed in this paper.

2. Experimental

The epitaxial Cu nanolines were prepared using an ebeam lithography method with double layer PMMA and copolymer resist system [17,18]. An intrinsic Si(100) wafer with resistivity larger than 10,000 Ω-cm was first coated with a layer of 150 nm copolymer (MMA(8.5)MAA) EL6 resist (MicroChem Corp.), followed by a layer of 100 nm 950 PMMA A2 resist (MicroChem Corp.). The patterns used for ebeam writing on the resist layer included pad (2.0 μm in diameter) and line (13.4 μm in length) periodical arrays, as described in a previous study [9]. The ebeam writing was conducted on a Zeiss Supra 55 SEM with Nabity Pattern Generation System. The resist with ebeam exposed patterns was developed in a Methyl Isobutyl Ketone (MIBK) solution (1 MIBK: 3 isoproponal) for 50–60 s with sonication. The PMMA nanotrenches were formed in this step. The sonication helped to remove the resist residues at the bottom of the trenches. Due to the higher ebeam sensitivity of the EL6 copolymer comparing to 950 PMMA A2, the resist development resulted in an undercut profile of the trench cross-section. The Si wafer with the patterned resist layer was then dipped in 10% hydrofluoric acid solution for 1 min to render the exposed Si surface hydrogen terminated. The substrate was immediately transferred to an ebeam evaporator for copper deposition at room temperature (Cu is 99.999% in purity obtained from International Advanced Materials). The thickness of Cu deposited was controlled at approximately 50 nm using a quartz crystal microbalance monitor. The substrate was finally immersed in acetone for 5 min to lift off the Cu on the top of the resist and was blown dried using nitrogen gas. The introduced undercut trench profile helped to achieve the clean and smooth edge on the Cu nanolines. The epitaxial property of the Cu pads and lines was examined using electron backscatter diffraction (EBSD) technique.

The electrical resistivity of the Cu nanolines was measured using a standard four-point probe method in a vacuum condition at room temperature. The tests were conducted in an SEM chamber (Zeiss ultra 1540 EsB). Zyvex nanomanipulation system was used to mount the SM-10 tungsten nanoprobes (Signatone Corp.) on four 2.0 μm Cu pads. The current–voltage sweeping experiments were carried out using a Keithley 4200 analyzer. The resistance of the Cu nanolines was calculated from the slope of the linear current–voltage plots. The experimental resistivity was then calculated based on the formula: $\rho = RA/L$, where ρ is the resistivity (μΩ·cm), R is the resistance measured (Ω), A is the cross-sectional area of the Cu line (nm^2), and L is the length of the Cu line (μm). The electrical tests were all conducted within two days after the Cu line fabrication process.

To obtain accurate information on the cross-section of the Cu nanolines, the geometry and dimensions of the cross-section were examined using FIB milling technique. The experiments were conducted in the Zeiss Ultra 1540 dual beam FIB/SEM system with 30 kV gallium ion beam. A 2.0 μm platinum layer was pre-deposited on top of the Cu lines for protection during the milling process. The cross-section imaging was carried out using a 2.5 kV electron beam.

To characterize the surface roughness of the Cu lines, a contact mode AFM (Park Scientific Autoprobe CP, Veeco Instruments) was employed to scan along, as well as across, the lines. The tip radius of the cantilever probe (MikroMasch) is ~8.0 nm with an aluminum coating on the backside of the cantilever. The scanning area was set at 1.0–2.0 μm with 512 × 512 scanning resolution.

To measure the LER, SEM micrographs of the top view of the Cu lines were acquired using a Zeiss Supra 55 with a 2.5–5.0 kV electron beam. The micrographs were then post-processed with ImageJ V1.47 software to extract the line edge information. The line width roughness (LWR) was then calculated based on extracted line edge data. The relationship between LER and LWR amplitude is $\sigma_{LWR}^2 = 2\sigma_{LER}^2$ (where σ is the standard deviation of either the LER or LWR), assuming that the two edges are uncorrelated [16].

3. Results and discussion

3.1. Cu nanoline fabrication and electrical test

SEM micrographs of fabricated Cu nanolines are shown in Fig. 1. The width of the Cu line ranges from 20 nm to 180 nm, and the height ranges from 40 nm to 50 nm. The line edge appeared to be clear of debris over the lift-off process. The metal debris is quite common when using the single layer resist fabrication method. It is due to the challenge of creating an undercut trench profile in a single thin layer resist [17,19,20]. Without an undercut profile, the metal deposited on the sidewalls tends to be reabsorbed to the metal lines during the lift-off process, and increases roughness on the line edge and the top surface. The absorbed metal debris will affect the electrical test results and consequentially the resistivity calculation. As shown in Fig. 1, the surface of the wider Cu line shows a typical surface texture of epitaxial Cu films [21], and is free of metal debris. The measured root-mean-square surface roughness (RMS) using AFM is around 0.5 nm. Previous works [9,21] have examined the epitaxial property of Cu films grown on the hydrogen terminated Si (100) substrate using X-ray pole-figure analysis and demonstrated a crystallographic orientation relationship of Cu(100)//Si(100) with Cu(010)//Si(011). In this work, EBSD (NordlysNano detector, Oxford Instruments) characterization using 20 kV incidence electron beam on the 50 nm thick Cu pads and Cu lines (180 nm) has been carried out. It further confirmed that no grain boundaries exist in the epitaxial Cu samples in contrast to a 50 nm polycrystalline Cu film grown on the same Si substrate without HF treatment (EBSD data not shown).

Experimental setup for the electrical test using four-point probe method is shown in Fig. 2. The figure includes an inset showing the zoom-in of the tungsten probe contacting one of the Cu pads. Probes 2 and 4 provide a current sweep through the Cu lines (ranging from 1.0 μA to 200 μA). Probes 1 and 3 measure the potential drop between the two adjacent Cu pads. All measurements show a linear response of voltage to current ramping, indicating an ohmic resistance behavior.

3.2. Resistivity estimation using rectangular cross-section profile

Based on the FS theory, Chambers developed a general formula to model the electrical resistivity of metal lines [22]. For purely diffuse surface scattering with specular factor $p = 0$, and an arbitrary line cross-section, the contribution of surface scattering to the resistivity can be expressed as [23,24]

$$\frac{\rho_0}{\rho_{FS}}(p=0,\lambda) = \frac{3}{4\pi s}\int_s \int_0^{2\pi} d\theta \int_0^{\pi} d\theta \sin\theta \cos^2\theta \left[1 - \exp\left(\frac{-L}{\lambda}\right)\right], \quad (1)$$