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Thermal characterization of copper thin films made by means of sputtering

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Copper thin films have been deposited onto Corning glass substrates by means of two kinds of DC magnetron sputtering. The goal of this research was to study differences in thermal characteristics of both kinds of the films. The differences between these layers originate from the technological processes; one of them employs an inert gas – argon – in the vacuum chamber, and the other is the so-called “pure” self-sputtering. Thermal characterization of the layers was performed using the scanning thermal microscopy (SThM) as well as a far field thermographical system.

Key words: *copper, magnetron; sputtering; scanning thermal microscopy*

1. Introduction

Copper metallization of on-chip multilevel interconnects became in last decade an industrial process for new generations of integrated circuits (IC). Copper, compared to aluminium, has a greater resistance to electromigration and a lower electrical resistivity resulting in improved electrical performance, reduced Joule heating and better heat transport. On the other hand, thermal properties of the copper thin films depend on impurities introduced in the process of fabrication [1–4]. This paper presents the results of thermal characterization of copper layers, focusing on the influence of argon impurities. A comparison will be made between Cu thin films obtained by a standard magnetron sputtering (under argon atmosphere) and a self-sustained magnetron sputtering (without any working gas).

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2. Magnetron sputtering

In the case of films obtained by the standard sputtering process, the argon gas, albeit indispensable in the process (argon mode), may be treated as undesirable impurity. It becomes a factor that essentially modifies the structure (the Thornton's zone model) and electrical parameters of the films deposited. The application of the self-sustained magnetron sputtering (SSS) allows depositing thin films without noble gas contamination, with a very high deposition efficiency [5]. In this mode of sputtering, the discharge is sustained by sputtered metal ions and the working pressure in the chamber is equal to the final pressure of vacuum set. The properties of films deposited in such a way may differ from those prepared under argon. The purity of self-sputtered Cu films depends on the purity of the target material and of rest gases only (argon pressure is equal to zero in Thornton's structure diagram). The absence of any working gas in the sputtering process means, on one hand, elimination of potential impurities in the film being deposited and, on the other hand, deposition of films under new „microgeometry" conditions of the target-to-substrate particle transport (no collision events with the working gas). To deposit Cu films in the self-sustained sputtering mode a very high target power density is necessary (even a few hundreds W/cm^2). Using the WMK-100 magnetron device, about 100 W/cm^2 is necessary to sustain the sputtering without argon presence (SSS) [6, 7].

3. Thermal characterisation

Our thermal characterization of both types of copper thin films employs two methods. One of them is the classical far field thermography [8–10]. An IR far field microscope was applied to determine the IR radiation from the Cu metallization at various sample temperatures. Using the calibration curve, the signals of the IR radiation emitted from the sample surface were processed into emissivity factors. Figure 1 shows the influence of argon impurities on the emissivity factor. In the case of 1 μm film this factor is grater than that in the case of 2 μm film.

Another kind of our experiments was performed using the scanning thermal microscope for measurements of thermal conductivity (diffusivity) of samples with high spatial resolution.

The invention of the scanning tunneling microscope (STM) [11] and the atomic force microscope (AFM) [12] allowed sub-micrometer and, at times, atomic scale spatially resolved imaging of surfaces. The spatial resolution of nearfield techniques (such as AFM) is only limited by the active area of the sensor (which in the case of STM may only be a few atoms at the end of a metal wire). First experiments in scanning thermal microscopy (SThM) were carried out by Williams and Wickramasinghe [13] who employed a heated thin-film thermocouple fabricated of a conventional STM tip. In 1994, Dinwiddie and Pylkki described first combined SThM/AFM probes which employed resistance thermometry to measure thermal properties [14, 15].

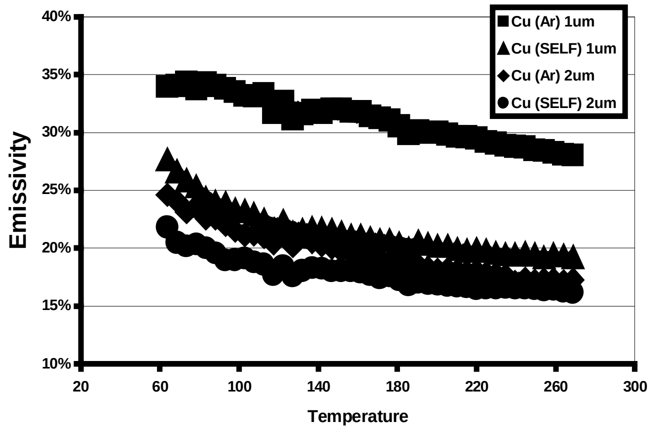

Fig. 1. Emissivity factor of the Cu samples versus temperature

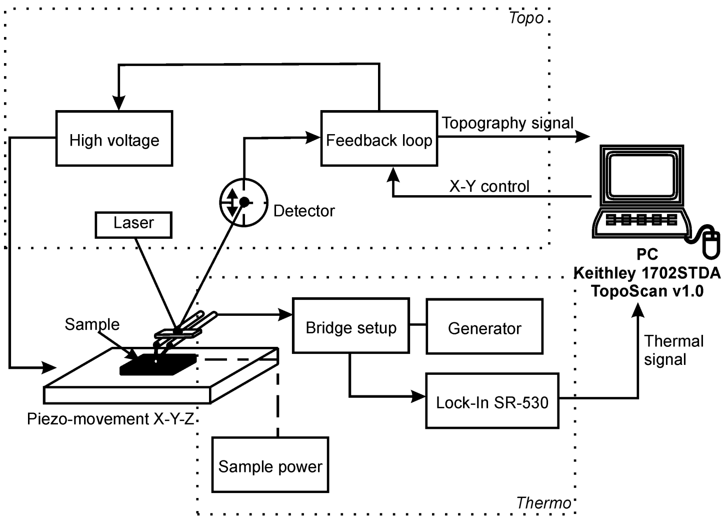

Fig. 2. Wollastone probe and block diagram of SThM system

The thermometers were fashioned and made of the Wollastone process wire, consisting of a thin platinum core (ca. 5 μm in diameter) surrounded by a thick silver sheath (ca. 75 μm). A loop of wire is formed and silver is etched away to reveal a small section of platinum which acts as a miniature resistance thermometer (Fig. 2a). Because of its high endurance, the Wollastone probe is attractive for micro- and nano-materials and microsystems diagnostic. The probe is capable of performing three functions: exerting a force on the sample surface (AFM), acting as a highly localized heat source (either constant or modulated), and measuring heat flow.

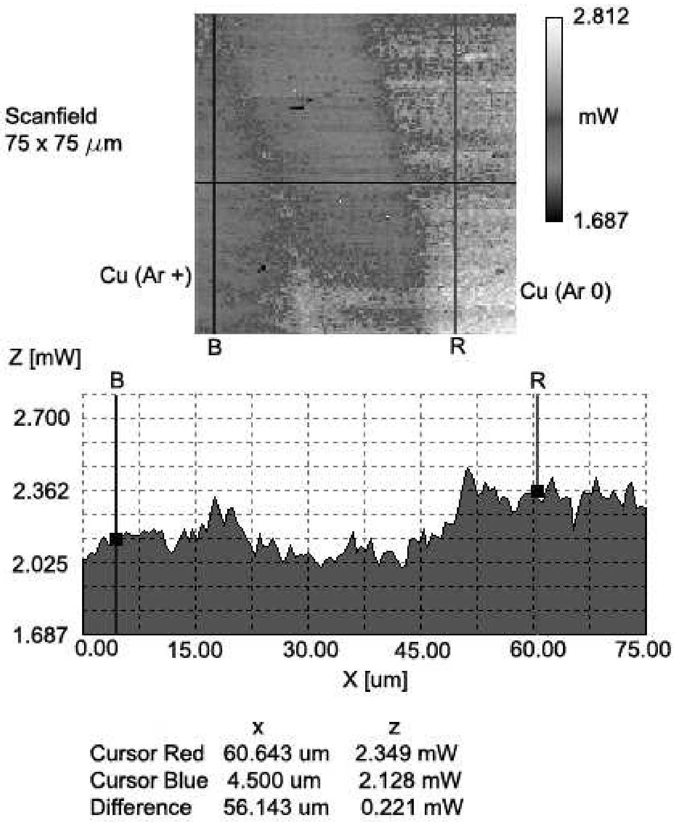

Fig. 3. Distribution of thermal conductance on Cu 0.5 μm films. Influences of Ar impurities in the layers are linked with difference of the signals on left (cursor blue B) and right (cursor red R) sites of the figure

The block diagram of our SThM apparatus is shown in Fig. 2b. The system can operate in two modes; as a passive thermosensing element (by measuring its temperature using a small current c.a. 500 μA) or as an active heat flux meter. In the latter case, a larger current (sufficient to raise the temperature of the probe above that of the surface – over 30 mA) is passed through the probe. The power required to maintain a constant temperature gradient between the tip and sample is monitored by means of an electrical bridge circuit. This power is related to the local thermal conductivity (diffusivity) of the sample [16, 17]. The SThM system allows us to measure local temperature with the thermal resolution 5 mK and thermal conductivity with the resolution of 10^{-2} W/mK. Dedicated software modules TopoScan and TopoGraf are used for measurement control and data processing [16].

The active mode of SThM is a promising method for thermal investigations of metals as well as of wide gap materials (i.e. GaN). A correlation between low threading dislocation density and high thermal conductivities was established [13]. We applied the SThM apparatus in active mode to measure local thermal conductivity of copper samples. Although the calibration procedure was not developed for copper samples in our system, it was nevertheless possible to use our microscope for the evaluation of local differences in values of thermal conductivity as well as of the geometrical topography of the sample as is shown in Fig. 3.

4. Conclusion

We applied our Scanning Thermal Microscope in active mode for the diagnostic of copper thin films. The measurements have been performed on two kinds of the Cu layers made by two kinds of magnetron sputtering. The topography and local diffusivity distribution shows the influence of argon impurities in the body of the Cu films. Thermal diffusivity can be determined with sub-micron spatial resolution.

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