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FORMATION AND MORPHOLOGY OF Cu NANOFILMS USING DC AND RF MODES OF A MAGNETRON SPUTTERING DEVICE

In this paper, we provide detailed information on the mechanism of formation of thin copper films in different modes of magnetron sputtering on the surface of single-crystal silicon by the solid-phase ion-plasma method. The dependence of the sputtering rate of Cu/Si films obtained by the direct current magnetron method and the radio frequency magnetron method on the sputtering time and the distance between the target and the substrate was studied. The surface morphology and electrophysical properties of thin copper films were analyzed. At a distance between the base and the target of 90 mm, the sputtering rate had a maximum value of 21 Å/sec. Polycrystalline films with a thickness of 90 nm and 110 nm were formed in the DCMS and RFMS modes in 2.5 minute. It was found that the DCMS mode is the optimal method for forming polycrystalline copper films. The RFMS mode can be used to form copper silicide films. These studies will serve as a basis for the formation of copper nanofilms used in the field of nanoelectronics in the future.

Keywords: magnetron sputtering, DCMS and RFMS, copper nanofilms.

1. Introduction

At present, the physical properties of nanoscale films and their alloys are of great interest, because the interconnection of electronic devices plays a leading role in the future of nanotechnology. Among some of the properties, the electrical resistance of nanoscale metal films can be highlighted, which mainly depends on the thickness and preparation conditions [1, 2]. In particular, metal alloys are of great importance for industrial applications due to their high corrosion resistance and mechanical properties [3]. The effect of film thickness and substrate temperature on the electrical and structural properties of copper films deposited by DC magnetron sputtering, as well as the effect of sputtering power and deposition pressure on the surface morphology have been reported in

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the literature [4]. The results show that the electrical and structural properties of copper films are generally improved with an increase in the film thickness and substrate temperature during the deposition process. Regarding the dependence of deposition power and deposition pressure, higher sputtering power and lower deposition pressure develop the microstructure of Cu films. In this research work, we will investigated the effect of argon pressure in DC magnetron sputtering on the crystal size of copper thin films deposited on p-type silicon (Si) substrate at room temperature. Furthermore, we discuss the conductivity of Cu film depending on Ar pressure in this paper. The effect of Ar pressure on the growth of Cu films on glass substrates has been reported recently, and this paper [4] focuses on the effect of Ar pressure on Cu thin films deposited on silicon substrates.

High-power pulsed magnetron sputtering (HiPIMS), radio frequency magnetron sputtering (RFMS), and direct current magnetron sputtering (DCMS) are solid-phase ionized plasma physical vapor deposition (PVD) methods [5–8]. Although the use of high pulsed ion current provides the desired film properties, one of its major drawbacks is that it typically has a lower deposition rate than RF and non-reactive DCMS. This is because the sputtered ions return to the target [9]. It has been previously reported that, for copper targets, this decrease in the deposition rate is in the interval of 25–65% [10–12]. The deposition rate of DCMS is significantly higher than that of HiPIMS. In addition, as the power increases, the voltage must be increased. The weakened magnetic "trap" of the magnetron is located far from the ionization zone of the target. As the voltage increases, the potential difference for ion extraction also increases, making manipulation of the magnetic "trap" ineffective. If the ion ionization is high, more energy is required to escape from this "trap", resulting in a decrease in the deposition rate. In this study, we used three different methods to determine the copper ion deposition rate. First, the film thickness was determined by measuring the difference in the initial and subsequent mass of the substrate. The second was measured using an Inficon SL-A0E00 quartz sensor (measurement accuracy 0.1) placed in a magnetron sputtering chamber and monitored on its monitor. Film thickness was measured using SEM to improve the accuracy of the obtained samples.

2. Preparation of Samples

Thin Cu films were deposited on the surface of a Si(111) single crystal from a copper target using the solid-phase ion-plasma method. The pressure in the sample deposition chamber was 1×10^{-5} Torr. The purity of the copper badges was 99.9999%, the diameter was 76.2 mm. The bases can be heated at room temperature to 400 °C. Ar (99.9%) was used as a working gas. The surface morphology of the films was studied using an Olympus LEXT$^{\text{TM}}$OLS5100 laser confocal microscope. Due to its advanced optical components, this microscope provides high-quality three-dimensional imaging, as well as fast and accurate measurements of surface shape and morphology at the submicron level. The thickness and elemental composition of the samples were measured using a SEC ALPHA scanning electron microscope. This microscope is a scientific scanning electron microscope with SE and BSE detectors, equipped with an EDS system from Oxford Instruments. The influence of deposition rate, thickness, sputtering current, deposition time and target-substrate distance on the obtained films was studied.

3. Results and Their Discussion

The deposition rate of copper films obtained by different sputtering methods is shown in Fig. 1. The deposition rate of copper atoms was determined using a radio-frequency magnetron sputtering setup with a pulse current mode of $D = 70\%$ and a frequency of 100 kHz. A parabolic change in the immersion rate is observed as the distance between the target and the base increases. The distance between the target and the substrate is equal to the maximum deposition rate of 80 Å/sec at $d = 88$ mm. The RFMS deposition rate varies depending on the distance between the substrate and the target and is used in the formation of thin films of copper silicide. It can be seen that the deposition rate of Cu ions from a copper target by the direct current magnetron sputtering method is almost the same in a wide interval from 33 mm to 142 mm (Fig. 1). At the same time, the data on the deposition rate of a copper target as a result of high-power pulsed magnetron deposition are presented in the work of Jake McLane [13] and others, and the distance between the substrate and the target is 6.2 cm and 12 cm, the rate is constant and equal to 42 Å/sec (Fig. 2).

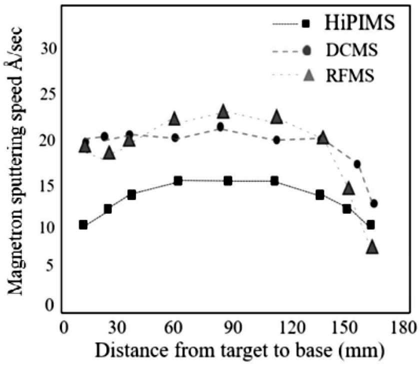

Fig. 1. Dependence of the copper target pollination rate obtained by different methods on the distance from the base to the target

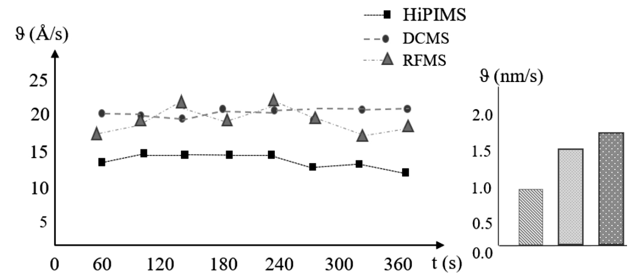

Fig. 2. Dependence of sputtering time on sputtering rate in different modes of magnetron sputtering

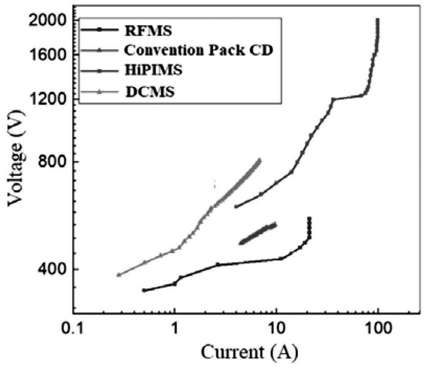

Fig. 3. Current-voltage curves of the standard and linear triple magnetron sputtering methods [13]

Elemental composition of Cu/Si nanofilm

Element	mass. %	σ, mass.%	atom. %
Si	0.34	0.02	0.76
Cu	99.66	0.02	99.24
Summa	100.00		100.00

A comparison of the current-voltage curves for the standard magnet stack and the linear triple magnet stack is shown in Fig. 3. The $n = 6$ configuration parameter is seen for the standard magnet stack, which is in the typical range [14]. The linear tripack has $n = 3$ configuration parameters, which is less than the standard magnet array, which is a desirable design feature since more electrons are required to escape the magnetic "trap". It can be seen that the HiPIMS increases rapidly with increasing voltage due to ion trapping. It was observed that at the top of the current-voltage curve there is a current limitation up to the average current limitation of the power supply [13].

Copper and copper silicide thin films of different thickness were deposited on a single-crystal silicon substrate by direct current and reactive frequency pulsed magnetron sputtering using a pure copper target in the presence of argon. The morphology of the films formed in different modes was studied by atomic force microscopy, electrical properties by four-point probe measurements, and the effect of silicide film formation with increasing thickness was studied by X-ray diffraction, respectively. The structural and electrical properties of the Cu films were systematically investigated as a function of temperature and substrate condition, showing that both parameters strongly affect the properties of the Cu thin films. Significant changes in the surface morphology of the films were also observed, caused by the film growth mechanism due to the change in film thickness. The promising physical properties of the copper thin films indicate their application in contact parts of thin-film solar cells and similar optoelectronic devices. Copper nanofilms of different thickness were formed by magnetron sputtering for 2.5 minutes at 250 °C in a vacuum of 10^{-5} Torr using the DCMS and RFMS methods. It showed that a 110 nm thick copper nanofilm was formed in the radio frequency mode, and a 90 nm thick copper nanofilm was formed in the direct current mode (Figs. 4 and 5). The SEM analysis showed that the DCMS mode produced higher quality nanofilms than the RFMS mode. The energy dispersive spectrum results for this sample (Fig. 6) confirm that a Cu nanofilm was deposited on the silicon surface. The SEM results are shown in Table for the percentage of atomic number and mass of copper nanofilms formed on the silicon surface.

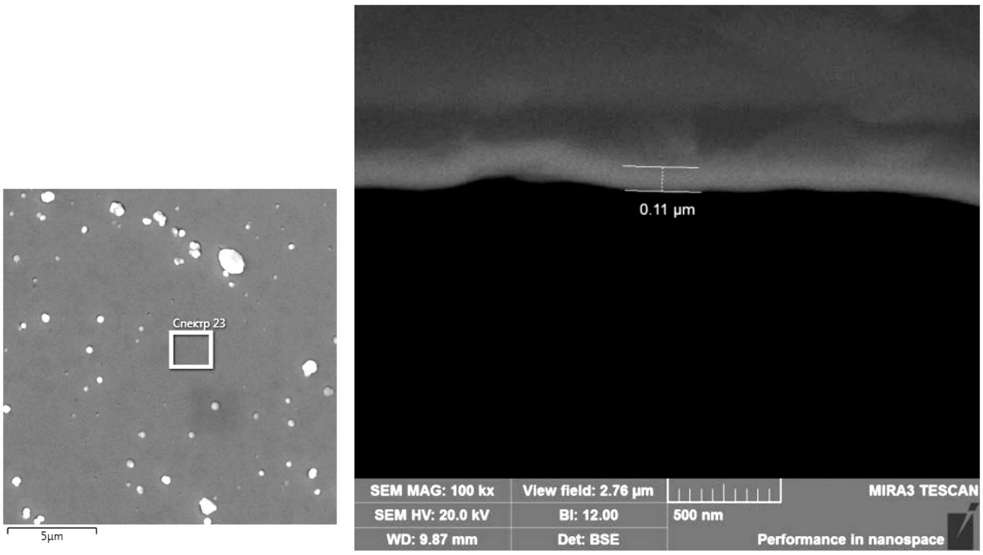

Fig. 4. SEM image of copper nanofilm formed by RFMS method

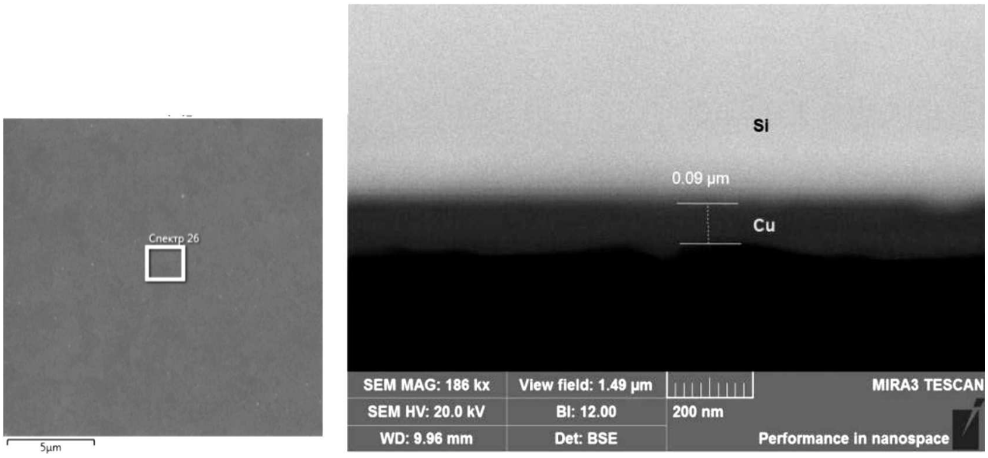

Fig. 5. SEM image of copper nanofilm formed by DCMS

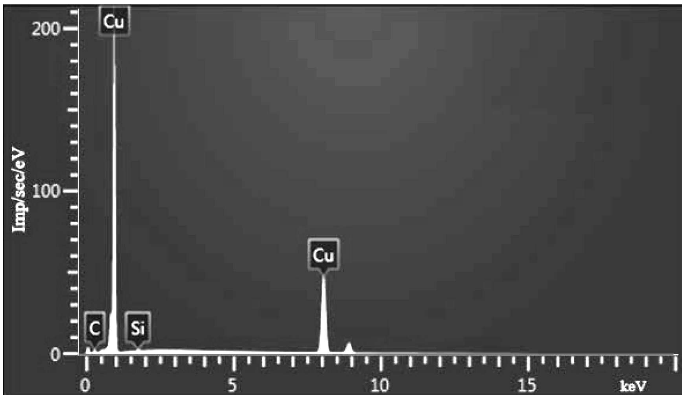

Fig. 6. Energy-dispersive spectrum of Cu/Si nanofilm

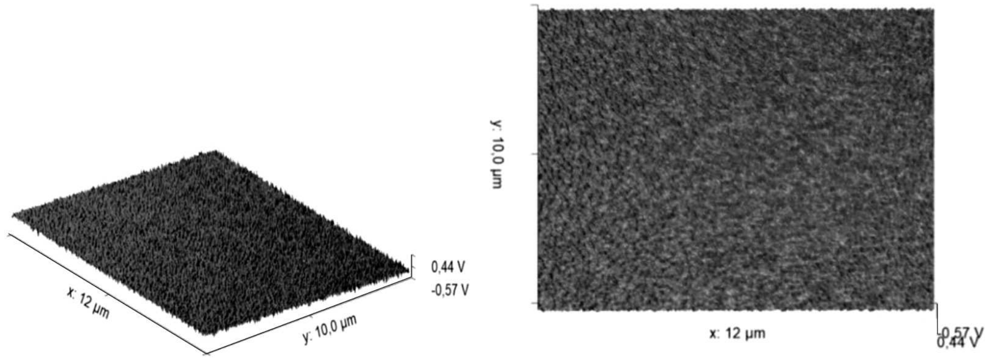

Fig. 7. 2D and 3D images of a Cu/Si (111) thin film

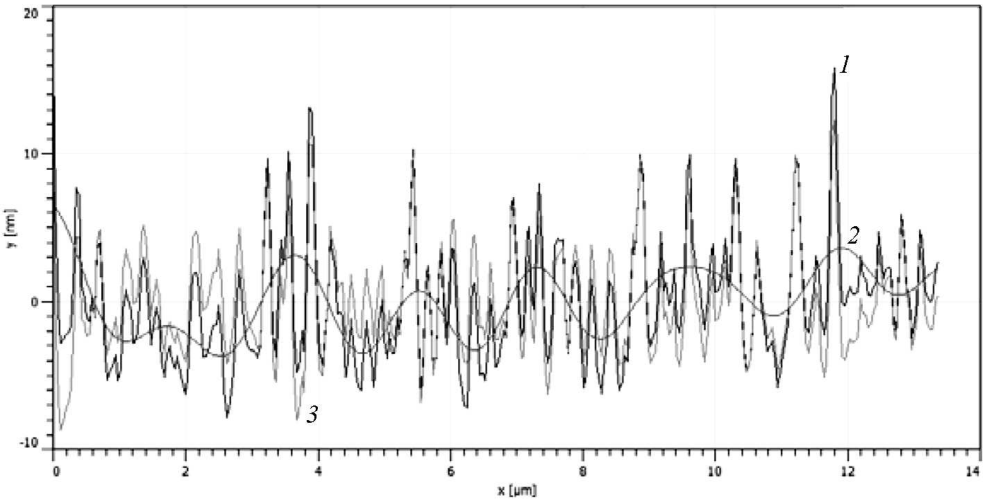

Fig. 8. Cu/Si film morphology measured by AFM. Texture, waviness and roughness

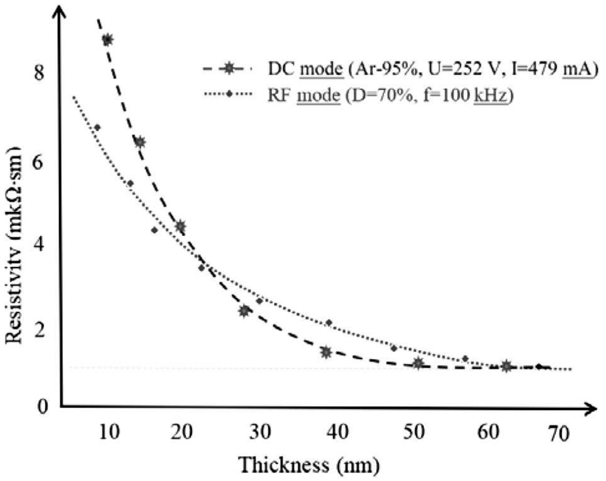

Fig. 9. Dependence of the thickness of the thin film formed in the RF and DC modes on the relative resistance

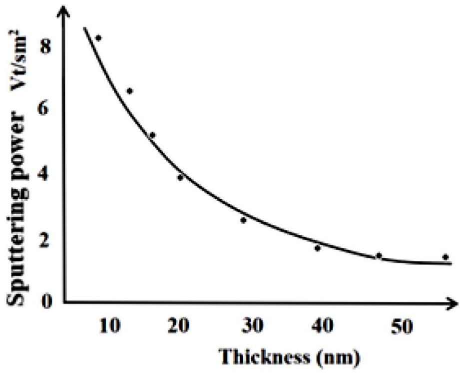

Fig. 10. Dependence of sputtering power on the thickness of the copper film formed in the constant current mode of the magnetron sputtering device

The surface morphology of the film obtained by magnetron sputtering with variable reactive frequency was studied. Figure 7 shows 2D and 3D images. It was found that a 110 nm thick Cu film was formed on the Si(111) surface as a result of constant power magnetron sputtering for 2.5 minutes. As a result of studying the morphology of the Cu/Si(111) film, it was found that its surface texture, waviness and roughness, are compatible with each other (Fig. 8).

AFM study of copper samples (10×12 μm) clearly showed that their surface morphology is strongly affected by the dependence of the magnetron sputtering mode. AFM images show that amorphous copper films are formed after radio frequency magnetron sputtering for 2.5 minute, which is consistent with the XRD results. Polycrystalline copper films were uniformly formed on the silicon surface after direct pulsed magnetron sputtering for 2.5 minute. The formation of films on the Si(111) surface by magnetron sputtering from a copper target by different methods is evidenced by the fact that it also depends to a sufficient extent on the substrate heating mode.

The dependence of the formed copper nanofilms on the film thickness was studied (Fig. 9). It was found that the specific resistance of Cu nanofilms in the DCMS mode does not change from 50 nm (Fig. 10). The dependence of the specific resistance of a thin Cu/Si (111) film on the sputtering power is shown. $\rho = 2$ μOhm $\cdot$ cm = const, $P = 2.8$ Vt/cm^2. The DCMS and RFMS methods are effective methods for the manufacture of integrated circuits, microsystems and multilayer materials. Integrated circuits are used in almost all electronic devices. These methods have many advantages: high deposition rate, high purity and homogeneity of the resulting films, high viscosity and high accuracy of thickness or grain size control of the resulting films. The main objective of this study is to determine the influence of various parameters of the copper metallization process on the parameters that have decisive consequences in electronic applications.

4. Conclusion

In this work, the formation of copper thin films from a copper target on the surface of monocrystalline silicon using radiofrequency and constant modes of the magnetron sputtering device, as well as the dependence of the sputtering rate on the distance between the target and the substrate, are investigated. At a distance between the base and the target of 90 mm, the sputtering rate had a maximum value of 21 Å/sec. Polycrystalline films with a thickness of 90 nm, 110 nm are formed in 2.5-minute DCMS and RFMS modes. It is found that the DCMS mode is the optimal method for the formation of polycrystalline copper films. The surface morphology and electrophysical properties of copper thin films are analyzed. The RFMS mode can be used in the formation of copper silicide films. These studies will serve as a basis for the formation of copper nanofilms used in the field of nanoelectronics in the future.

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ВИГОТОВЛЕННЯ ТА МОРФОЛОГІЯ МІДНИХ НАНОПЛІВОК З ВИКОРИСТАННЯМ ПРИЛАДІВ НА ПОСТІЙНОМУ СТРУМІ ТА РАДІОЧАСТОТАХ ДЛЯ МАГНЕТРОННОГО РОЗПИЛЕННЯ

Надається детальна інформація про механізм створення тонких (90 та 110 нм) мідних плівок на поверхні монокристала кремнію в різних модах магнетронного напилення твердофазним іонно-плазмовим методом. Досліджено залежність швидкості напилення плівок Cu/Si, отриманих магнетронним методом постійного струму та радіочастотним магнетронним методом, від часу напилення та відстані між мішенню та підкладинкою. Проаналізовано морфологію поверхні та електрофізичні властивості тонких мідних плівок. Для відстані між основою та мішенню, рівною 90 мм, швидкість напилення мала максимальне значення 21 Å/с. Полікристалічні плівки товщиною 90 нм та 110 нм були сформовані в режимах DCMS та RFMS за 2,5 хвилини. Виявлено, що режим DCMS є оптимальним методом для формування полікристалічних мідних плівок. Режим RFMS може бути використаний для формування плівок силіциду міді. Ці дослідження слугуватимуть основою для формування мідних наноплівок, що використовуються в галузі наноелектроніки в майбутньому.

Ключові слова: магнетронне напилення, постійний струм, радіочастота, мідні наноплівки.