Eur. Phys. J. Appl. Phys. (2012) 59: 10801
DOI: 10.1051/epjap/2012110306

THE EUROPEAN PHYSICAL JOURNAL APPLIED PHYSICS

Regular Article

Influence of copper thin film as an electrode on the DC electrical breakdown in the presence of Ar and air

K. Yasserian[a], R. Zaresirous, and A. Hojabri

Department of Physics, Karaj Branch, Islamic Azad University, Karaj, Iran

Received: 30 July 2011 / Received in final form: 22 April 2012 / Accepted: 25 June 2012
Published online: 3 August 2012 –

Abstract. Electrical breakdown for low pressure argon gas and air, using copper thin films as the electrodes, was investigated. A specially designed cathode was built from copper thin film deposited on glass by a magnetron sputtering system creating the breakdown between those electrodes. The left side of Paschen's curve and ionization coefficient η as well as the effective electron emission coefficient γ was obtained with respect to the variation of reduced electric fields for argon gas and air for different thin films thicknesses. It is concluded that reducing the thin film thickness as an electrode leads to a decrease of breakdown voltage and amplifying secondary electron emission. In addition, the influence of the gas type on dependence of breakdown characteristics on the electrode thickness was investigated.

1 Introduction

Electrical discharges have wide industrial applications in many fields such as electronic, semiconductors, light sources, plasma surface modifications, analytical spectrochemistry, ion sources, and deposition by sputtering [1]. The minimum voltage in which a phase transition occurs from a non-conducting material into an electrical conductor as a result of using a strong enough electric field is known as the electrical breakdown voltage. Understanding the breakdown mechanisms is necessary in many technologies such as plasma display panels, electrical devices, lasers and nanotechnology and has recently been investigated in many papers theoretically and experimentally [2–8].

Generally, the electrical breakdown depends on the working gas type and electrode geometry as well as the electrode material features [9,10]. The electrical breakdown of a gas can occur when enough ionizing collisions take place between electrons and a neutral background gas. It is a transition from a non-self-sustained to a steady self-sustained current in the Townsend discharge. The first Townsend coefficient α determines the number of ionization events per length by an electron and can be given by the following relation [11,12]:

$$\alpha = Ap\exp(-Bp/E), \tag{1}$$

where p and E represent the pressure and electric field, respectively. The constants A and B depend on the gas type which are inversely proportional to electron temperature and also depend on the ionization cross-section [13,14]. The ionization coefficient η represents the ionization capability of electrons and can be introduced as $\eta = \frac{\alpha}{E}$ which depends on the reduced electric field. Another important quantity in understanding the breakdown is the effective secondary electron emission γ which depends on the gas type and target material in the following relations:

$$\gamma = \frac{1}{e^{\eta V_B} - 1}, \tag{2}$$

$$V_{\min} = \frac{\bar{e}B}{A}\ln(\frac{1}{\gamma} + 1), \tag{3}$$

$$(pd)_{\min} = \frac{\bar{e}}{A}\ln(\frac{1}{\gamma} + 1). \tag{4}$$

The reduced electric field E/p at the minimum value corresponds to the minimum energy which is consumed to create one pair of ions where the ionization capability of electrons $\eta = \frac{\alpha}{E}$ is equal to $\frac{A}{B\bar{e}}$ with $\bar{e} \approx 2.72$ as the maximum. The values of $V_{\min}$ and $(pd)_{\min}$ depend on the cathode features (γ) and are estimated by equations (3) and (4).

The characteristics of secondary electron emissions γ for various metals under different projectile collision (ion, electron, photon and atom) have been investigated in references [15–21]. Moreover, the ion- and atom-induced secondary electron emission coefficients for dirty and clean surface targets have been investigated in glow discharge [22]. In addition, the surface condition is a key response to the electron emission but there is no experimental evidence to treat the thin films as electrodes for creating electrical breakdown. Recently, Depla et al. [23]

[a] e-mail: kiomars.yaserian@kiau.ac.ir

studied the influence of ion-induced electron emission coefficient and found its dependence on kinetic emission mechanisms. Since the stopping cross section for oxygen is lower than the metal cross section, the coefficient decreases by increasing oxygen content. The electron emission mechanism for metal in Townsend discharge differs and mainly depends on potential emission mechanism as well as the work function and Fermi energy. It should be added that dependence of work function on the thicknesses of thin film has been studied using different methods [24,25]. In reference [26], a thickness-dependent work function was investigated. Although the work function has influence on secondary electron emission, the influence of the film thickness on the electrical breakdown mechanism is not investigated directly.

In the current study, we investigate the dependence of electrical breakdown on the electrode material where the electrodes are copper thin films deposited on glass in the presence of argon and air. The structure of the paper is as follows. In Section 2, we present the experimental setup while in Section 3 the obtained results for different conditions are presented. We conclude the paper with a summary of the results in Section 4.

2 Experimental setup

A Pyrex glass tube 12 cm interior diameter and 14 cm in height, closed by aluminum plates and sealed by rings, was used as a chamber of discharge. The chamber was evacuated to a base pressure lower than 10^{-5} Torr with a diffusion pump backed up by a rotary vane pump. Argon gas with 99.9% purity has been flown and controlled by a needle valve. The gas pressure during breakdown was measured with a Penning gauge. All conducting parts in the chamber (rods and electrodes) were capsulated by an insulator, except the surface of the electrodes. Two external resistances (1.2 kΩ) were used to limit the discharge current in order to protect the measuring instrument and ensure that the discharge would be limited to the Townsend regime, as well as for detecting the electrical breakdown transition by measuring the drop potential across the resistors. A schematic diagram depicts in Figure 1.

The interelectrode gap for the set of experiments was fixed to 3 cm. The electrodes were 25 mm in diameter for all samples. The copper thin films were coated on the glass substrates using DC magnetron sputtering with copper targets of 99.95% purity. The working sputtering pressure and related electrical discharge power were 0.03 Torr and 100 W, respectively. The thickness of the deposited films for 1 and 10 min was 45 nm and 415 nm in that order. In addition, by using atomic force microscopy analyses, the uniformity across the entire surface of the cathode had been obtained and surface morphology analyses showed that the root mean-square roughness of the films was 1.065 nm and 8.45 nm for the thicknesses of 45 nm and 415 nm, respectively. As copper is strongly reactive, oxidation may take place during the experiment. However, since the experiments were performed over a fairly short time period, the composition of the deposited film as the cathode and sputtering target is nearly the same which was verified by energy-dispersive X-ray spectroscopy (EDX) analysis. By using EDX, the purity of the deposited film was shown to be 99.95% and there were negligible values of elements such as Ni, As, Sb, Sn, Pb, Fe and Bi present. The coated copper thin films were considered as the electrodes and the thin connectors were used to connect the surface electrodes to the power supply.

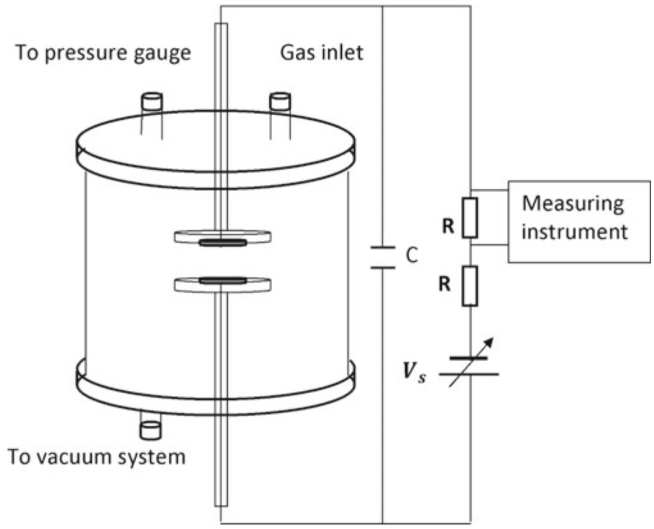

Fig. 1. Schematic diagram of the discharge tube and measuring circuit.

3 Results

Figure 2 shows Paschen's curves for different copper thin films thicknesses in the presence of argon gas. It is observed that the electrical breakdown voltage decreases as a whole by reducing the thin film thickness, while values of *pd* corresponding to the minimum electrical breakdown voltage of curves have little variation.

In Figure 3, Paschen's curves for different copper thin films thicknesses are shown in the presence of air and it can be seen that the effect of film thickness is more pronounced at low pressures. The decrease in the breakdown voltage by reducing the film thickness can be a consequence of the variations of the work function in respect to the thickness. On both sides of the minimum in Paschen's curve, the breakdown voltage increases due to the deviation from threshold conditions or effective ionization cross section. In contrast to the right side of the minimum, in the range of low pressures and on the left side of Paschen's curve, the possibilities of collisions are restricted, so the breakdown voltage promptly grows by decreasing the values of *pd* [27]. At low pressure, the secondary electron emission mechanism takes an effective part in the breakdown phenomena, therefore on the left side of the minimum breakdown of Paschen's curve, the breakdown is governed by the electrode material properties rather than by the ionization process in the bulk of gas [28].

By comparing Figures 2 and 3, it can be concluded that the gas type has a similar influence on the

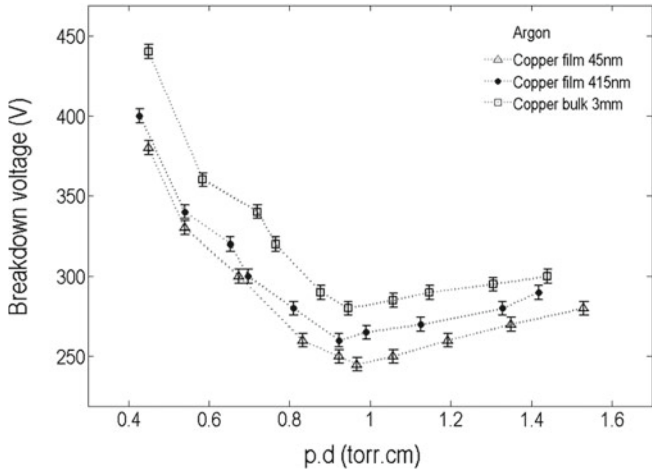

Fig. 2. Paschen's curve for argon gas using copper thin films electrodes.

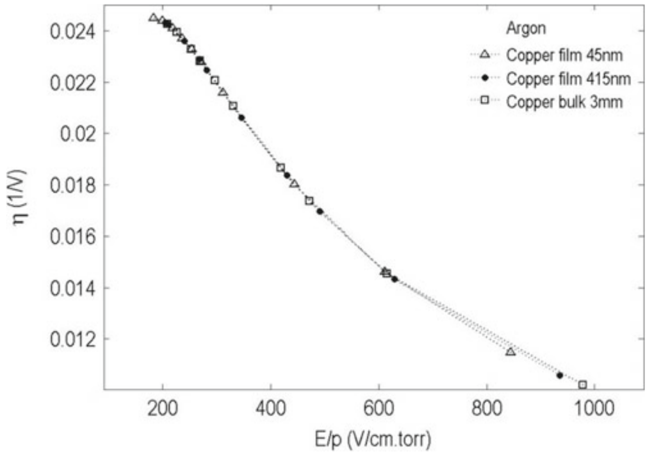

Fig. 4. The ionization coefficient as a function of reduced electric field E/p in the presence of argon for three types of electrodes.

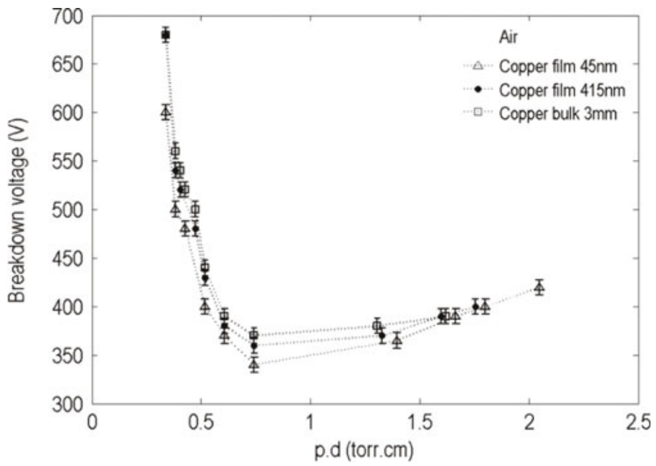

Fig. 3. Paschen's curves for air using copper thin films electrodes.

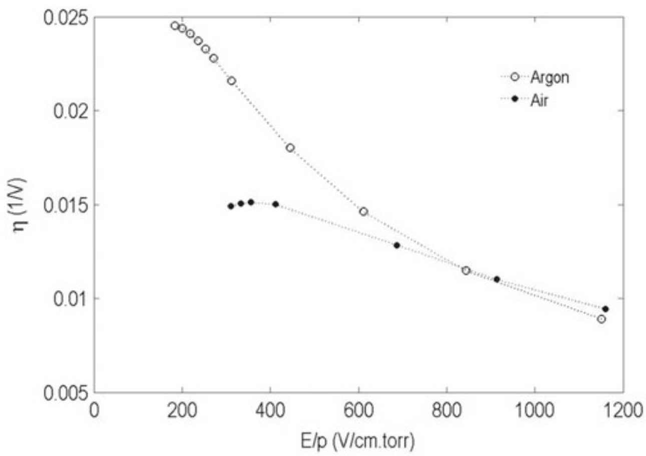

Fig. 5. The ionization coefficient as a function of reduced electric field E/p for air and argon gas.

dependence of the breakdown voltage on the copper thin film thicknesses. They show that electrical breakdown voltage decreases in the minimum and fairly on the left side of the curves by reducing the thickness. However, in the presence of argon gas, the values of pd corresponding to the minimum voltage are greater with respect to the air.

The ionization coefficient η is estimated by using proper A and B consonants. Figure 4 demonstrates the ionization coefficient η as a function of a reduced electric field for different electrode thicknesses for argon discharge. It can be seen that the electrode features have no influence on the ionization coefficient and increasing the reduced electric field leads to the decreasing of the coefficient. According to reference [12], the ionization coefficient depends on the gas type and consequently the thickness of the electrode does not lead to variations of η.

In Figure 5, the ionization coefficient is calculated as a function of reduced electric field for argon and air. This figure shows that the ionization coefficient of argon gas has a higher value when compared to air in low E/p where the difference of η between argon and air diminishes in high E/p. In this region as expected, the breakdown characteristics are governed by the electrodes features.

To understand the influence of copper thin film as electrodes, the effective secondary electron emission coefficient γ is obtained for various thicknesses. In Figure 6, the quantity of γ is plotted as a function of the reduced electric field for three copper thin film thicknesses and it can be seen that increasing the reduced electric field results to amplify the secondary electron emission coefficient leads to a decreasing of the breakdown voltage. In addition, it can be concluded that in the middle ranges of the reduced electric field, the influence of electrode thickness is more pronounced and the difference between the bulk and thin film electrode is more apparent in the condition of high energetic electrons.

In Figure 7, the effective secondary electron emissions are plotted versus the reduced electric field in the presence of air for values of copper thickness. Since the minimum of the pd values in Paschen's curve for air is lower than for argon gas, the range of reduced electric field in Figures 6 and 7 is not the same. As can be seen again in

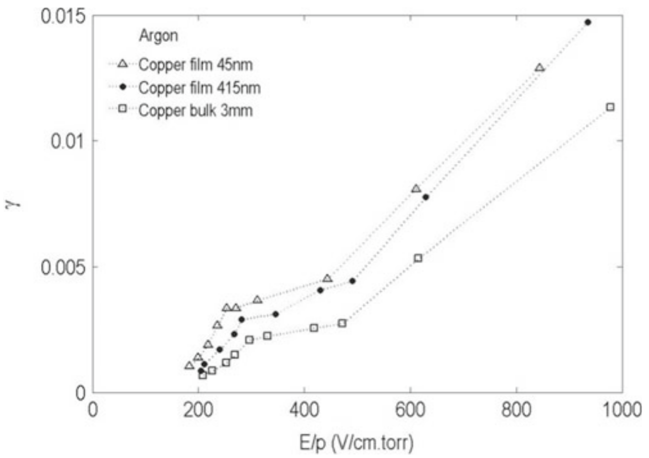

Fig. 6. The effective secondary electron emission coefficient γ as a function of the reduced electric field E/p using copper thin films electrodes for argon gas.

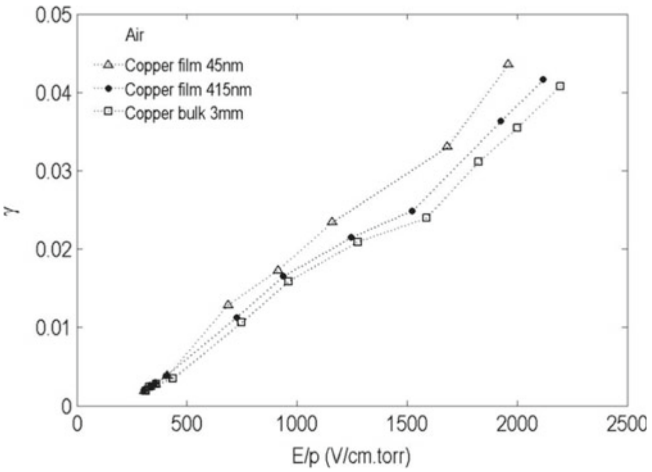

Fig. 7. The effective secondary electron emission coefficient γ as a function of the reduced electric field E/p using copper thin films electrodes for air.

this comparison, the copper thin film with a small thickness has a high value of secondary electron emission in the presence of air.

In the low reduced electric field E/p, the mean electron energy is low and the excitation within the gas has more probability than ionization, so photoelectric emission from the cathode will occur. As the E/p rises, the excited atoms increase and there is a reduction in photoelectric emission. In this condition, the secondary electron emission is governed by potential emission, and therefore strongly depends on the work function and Fermi energy of the cathode. In higher E/p region, the domination of the secondary process is mainly due to the impact of ions on the cathode or dynamics of the charged particles.

4 Conclusion

The copper thin films were used as electrodes for electrical breakdown characteristics and the influence of the thickness on the breakdown voltage and ionization coefficient as well as secondary electron emission was investigated in the presence of two gases: argon and air. The results have shown that the copper films deposited on the glass have a higher secondary electron emission than bulk metal and that thinner films have the higher secondary electron emission, especially in the middle range of E/p. The electrical breakdown voltages of the thin film and the bulk material were compared and it was concluded that by decreasing the film thickness, the breakdown voltage diminishes. This can be attributed to a smaller work function of thin film in contrast to the bulk metal. As the results of the ionization coefficient indicate in middle and high region E/p, the breakdown characteristics are governed by the electrodes features and the influence of air and argon in the breakdown voltage in comparison to the film thicknesses are not significant.

References

1. A. Bogaerts, E. Neyts, R. Gijbels, J. Van Der Mullen, Spectrochim. Acta Part B **57**, 609 (2002)
2. T. Dufour, L.J. Overzet, R. Dussart, L.C. Pitchford, N. Sadeghi, P. Lefaucheux, M. Kulsreshath, P. Ranson, Eur. Phys. J. D **60**, 565 (2010)
3. G. Bingang, L. Chunliang, S. Zhongxiao, F. Yufeng, X. Xing, L. Liu, F. Duowang, Eur. Phys. J. Appl. Phys. **31**, 185 (2005)
4. X. Cai, X. Zou, X. Wang, L. Wang, Z. Guan, W. Jiang, Laser Part. Beams **28**, 443 (2010)
5. F. Ghaleb, W. Benstaali, A. Belasri, Mater. Sci. Eng. C **28**, 791 (2008)
6. B.N. Sismanoglu, J. Amorim, Eur. Phys. J. Appl. Phys. **41**, 165 (2008)
7. S.N. Stamenković, V.Lj. Markovic, S.R. Gocić, Eur. Phys. J. Appl. Phys. **45**, 11003 (2009)
8. V.Lj. Markovic, S.R. Gocić, M.K. Radović, Eur. Phys. J. Appl. Phys. **6**, 303 (1999)
9. M.M. Pejovic, G.S. Ristic, J.P. Karamarkovic, J. Phys. D: Appl. Phys. **35**, R91 (2002)
10. H. Raether, *Electron Avalanches and Breakdown in Gases* (Butterworths, London, 1964)
11. E.D. Lozansky, O.B. Firsov, *Theory of Sparks* (Atomizdat, Moscow, 1975)
12. A. von Engel, *Handbuch der Physik* (Springer, Berlin, 1956)
13. A.L. Ward, J. Appl. Phys. **33**, 2789 (1962)
14. A. von Engel, *Ionized Gases* (Clarendon, Oxford, 1965)
15. G. Auday, P. Guillot, J. Galy, H. Brunet, J. Phys. D: Appl. Phys. **83**, 5917 (1998)
16. J.M. Meek, J.D. Graggs, *Electrical Breakdown of Gases* (Clarendon, Oxford, 1953)
17. S.C. Brown, *Basic Data of Plasma Physics* (MIT Press, Cambridge, MA, 1959)
18. R.A. Baragiola, E.V. Alonso, O.A. Florio, Phys. Rev. B **19**, 121 (1979)
19. A. Koyama, T. Shikata, H. Sakairi, Jpn J. Appl, Phys. **20**, 65 (1981)

20. G. Lakits, A. Arnau, H. Winter, Phys. Rev. B **42**, 15 (1990)
21. A.V. Phelps, Z.L. Petrovic, Plasma Source Sci. Technol. **8**, R21 (1999)
22. A. Bogaerts, R. Gijbels, Plasma Source Sci. Technol. **11**, 27 (2002)
23. D. Depla, H. Tomaszewski, G. Buyle, R. De Gryse, Surf. Coat. Technol. **201**, 848 (2006)
24. R.J. Batt, C.H.B. Mee, J. Vac. Sci. Technol. **6**, 737 (1969)
25. H. Hoffmann, H. Hornauer, U. Jacob, J. Vancea, Thin Solid Films **131**, 1 (1985)
26. J. Vanecea, G. Reiss, D. Butz, H. Hoffmann, Europhys. Lett. **9**, 379 (1989)
27. Y. Nunes, A. Wemans, P.R. Gordo, M. Ribeau Teixeira, M.J.P. Maneira, Vacuum **81**, 1511 (2007)
28. G. Petraconi, H.S. Maciel, R.S. Pessoa, G. Murakami, M. Massi, C. Otani, W.M.I. Uruchi, B.N. Sismanoglu, Braz. J. Phys. **34**, 4B (2004)