Nb thin films fabricated by a magnetic flux distribution variable-type facing target sputtering system

S. Morohashi, Y. Masumoto, K. Tanaka, K. Usui and Y. Kuzuo

Faculty of Engineering, Yamaguchi University, 2-16-1 Tokiwadai, Ube 755-8611, Japan

E-mail: smoro@yamaguchi-u.ac.jp

Abstract. A magnetic field distribution variable-type facing target sputtering system has been newly devised. The magnetic field distribution between facing targets can be easily changed by moving a magnet without breaking the vacuum. By changing the magnetic field distribution between facing targets, Niobium deposition rate has changed about five times with the same sputtering conditions, such as RF applied electric power and Ar pressure.

1. Introduction
Among thin-film deposition techniques, sputtering is widely used for the fabrication of electronic devices with multilayer film structures, such as displays, solar batteries, and ferromagnetic or superconducting tunneling junctions in which electrons tunnel through a barrier of about 1-nm thickness, [1,2]. In recent years, for solar batteries and image displays in which thinner structures are preferred, there has been increasing demand for multilayer electronic devices to be fabricated on organic films instead of hard and heavy glass substrates, in order to realize lightweight, low-cost, and flexible systems [3]. For the fabrication of tunneling devices and devices with multilayer film structures for film-based electronics and displays, we require a so-called low-temperature sputtering technology that can realize clear interfaces without any damage to the heat-sensitive substrate and the interfaces between layers during film deposition [4][5]. The conventional facing-target sputtering system is characterized by low damage because of the unique cathode structure, in which γ electrons are not incident on the substrate surface [6]. However, when compared with the widely used magnetron sputtering system, it became clear that the challenge was to improve both its (a) compactness and (b) through-put.

2. Facing-target sputtering system with new functions
2.1 Comparison between magnetron sputtering and conventional facing-target sputtering
Figure 1 shows a comparison between magnetron sputtering and conventional facing-target sputtering in terms of the damage to Teflon tape when a Si substrate is wrapped with Teflon tape and a SiO₂ film is deposited at approximately the same deposition rate (13.0 nm/min) [7]. Using magnetron sputtering, damage was observed in the Teflon tape after 7 min and 40 s from the start of sputtering (see Figure
1(c)). In contrast, when using the conventional facing-targets sputtering technique, the shape of the Teflon tape was still retained after 21 min and 30 s (see Figure 1(d)). As shown schematically in Figures 1(a) and (b), in normal magnetron sputtering in which the substrate faces the target, there is a structurally high probability that the electrons (γ electrons), which are released by ion bombardment of the target surface and the recoiled Ar ions, will hit the substrate; the deposited film is then damaged when these high-energy particles are incident on the substrate. In contrast, in the conventional facing-targets sputtering system, as shown schematically in Figure 1(b), the magnet is placed right in the back of the target, so that there are opposite magnetic poles between the facing targets; therefore, the γ electrons and the resulting plasma are confined in the space between the targets, and the deposited film is not damaged because the γ electrons are not incident on the substrate surface [6]. It is thought that the difference in the damage to Teflon, as shown in Figs. 1(c) and (d), reflects this difference in the cathode structure.

![Diagram](image)

Fig. 1 Schematic illustration of the damage caused by magnetron sputtering and conventional facing-target sputtering. (a) Schematic diagram of magnetron sputtering. (b) Schematic diagram of conventional facing-target sputtering. (c) Surface state of Teflon tape after 100 nm-thick SiO2 film deposition by magnetron sputtering. (d) Surface state of Teflon tape after 300 nm-thick SiO2 film deposition by conventional facing-target sputtering.

2.2 Revolving-type facing-target sputtering system with multi-target

The volume of the cathode in conventional facing-target sputtering does not pose a problem in the case of single-target sputtering for the deposition of a single-layer film. However, in the case of multi-target sputtering for the continuous deposition of multilayer films, the multiple parallel-facing structures requires a larger cathode capacity and a larger vacuum pump; the system therefore has high initial and running costs, that is, it is uneconomical in terms of energy usage and is rather large. The revolving facing-target sputtering system was devised to enhance the compactness while causing little damage, as is characteristic of facing-target sputtering systems [7][8]. Figure 2 shows a schematic diagram of a sputtering system with four targets. The magnets in each revolving facing cathode-box form a closed magnetic circuit, and the magnets of the facing sides of a revolving facing cathode-box have opposite magnetic poles. Four targets are installed on the outer side of each revolving facing cathode-box. Compact sputtering with multi-target is realized by revolving these facing cathode boxes.
Figure 3 shows the revolving facing-target sputtering system with six targets fabricated in the Consortium R&D Project for Regional Revitalization from METI in 2005-2006 [9]. The inset shows a schematic diagram of the revolving facing cathode-box with six targets within the chamber. The total cathode capacity of the system is estimated to be less than about one third of that for conventional facing-targets sputtering with six targets, and the system is advantageous from the viewpoint of energy economy and compactness.

Fig. 2 Schematic diagram of the revolving facing cathode-box in the revolving-type facing-target.

Fig. 3 Revolving facing-target sputtering system with six targets fabricated in the "Development of a new low-temperature sputtering system for organic electroluminescence electrodes and passivation films" (Principal investigator: Shinichi Morohashi, Yamaguchi University), the Consortium R&D Project for Regional Revitalization from METI, 2005-2006.
2.3 Magnetic flux distribution variable-type facing-target sputtering system

Figure 4 shows the magnetic flux distribution variable facing-target sputtering system devised to realize high-speed deposition for improved throughput, while satisfying the requirements for low damage [10] [11]. The system can increase the degrees of freedom of sputtering, that is, sputtering can be achieved under different magnetic flux distribution between facing-target, where the magnetic flux distribution is controlled with a moving rod magnet without breaking the vacuum. This idea defies the conventional notion of "one cathode, one sputtering system." Figure 4 shows the cross-section of a facing-cathode, with moving rod magnets that change a magnetic flux distribution between facing-target; the use of a moving yoke [11] or an electromagnet would also be possible.

The outer stationary cylindrical magnets are of the type also found in the conventional facing-target sputtering system. The facing cylindrical magnets are of opposite magnetic poles; in the figure, the cylindrical magnet in the back of the left target is an N-type magnet, and that in the back of the right target is an S-type magnet. The bar magnets in the middle are moving magnets; the cylindrical magnets and the moving magnets have opposite magnetic poles at the back of each target. With such a magnet arrangement, three magnetic flux distributions are created: (1) a magnetic flux distribution between the facing-target due to the facing cylindrical magnets; (2) a magnetic flux distribution between the facing-target due to the facing moving rod magnets, directed oppositely to the field created by the cylindrical magnets; and (3) a magnetic field distribution directed from the N to S magnetic poles, as found in magnetron sputtering, created by the stationary cylindrical magnet and the moving rod magnet at the back of each target. The magnetic flux distributions (1), (2), and (3) between the facing-target can be controlled by the positions of the moving rod magnets without breaking the vacuum. The magnetic flux distribution is shown schematically for the two cases in Figure 4. Figure 4(a) shows the case where the magnetic flux distribution of (1) is strong, and Figure 4(b) shows the case where the magnetic flux distributions of (2) and (3) are added to the distribution of (1).

Fig. 4 Schematic diagram of the magnetic flux distribution between facing-cathode in magnetic flux distribution variable facing-target sputtering.
(a) Magnetic flux distribution when the moving rod magnets are farthest from the targets, (b) Magnetic flux distribution when the moving rod magnets are nearest to the targets.
magnetic flux distributions of (2) and (3) can be controlled continuously by the positions of the moving rod magnets (2).

Nb, a high melting point metal was used as a target (purity 3N and diameter 90 mm \( \phi \)), and the Nb deposition rate and the substrate temperature were evaluated as a function of the positions of the moving rod magnets under the conditions of Ar pressure of 0.7 Pa, RF applied power of 1 kW, and with a 10-cm distance from a target center to a substrate. Kapton tape was stuck on the silicon substrate, and a thermo label heater was stuck underneath the substrate; the film thickness and the substrate temperature were then measured simultaneously. The deposition rate was calculated by the ratio of the deposited film thickness over the sputtering time (2 min). The substrate temperature was the temperature measured without the use of cooling water. The moving rod magnet was moved within the 99-mm range of moving distance as measured from the origin, which was defined by the closest position of the moving rod magnet to the back of the target. Figure 5(a) corresponds to the magnetic flux distribution shown in Figure 4(a), where electric discharge plasma was observed similarly to that found in conventional facing-target sputtering. Figure 5(b) corresponds to the magnetic flux distribution shown in Figure 4(b), where the electric discharge plasma with a ring erosion area, as found in magnetron sputtering, was observed right at the front of the facing-target. The behavior depends on the variation of the magnetic flux distributions (1), (2), and (3) between the facing-target through the movement of the moving rod magnets.

The deposition rate changed by a factor of approximately five, from 50.3 nm/min to 11.0 nm/min, and the substrate temperature changed from 110°C to 40°C (see Figure 6) [12] [13]. The deposition rate and substrate temperature were highest at the position in which the magnetic flux distribution (3) was strongest, at the moving distance of zero. The deposition rate and substrate temperature became small in the region where the influence of the magnetic flux distribution (3) became small. It is considered that the variation in the magnetic flux distribution between the facing-target influences the electron density between the plasmas, the ionization density of the Ar gas, and the energy of the sputtering particles, ultimately changing the Nb deposition rate and the substrate temperature.
3. Conclusion

A magnetic flux distribution variable facing-target sputtering system was developed to control the magnetic flux distribution between facing-target by using moving magnets. We could change the deposition rate of a high-melting-point metal (Nb) by a factor of approximately five simply by changing the magnetic flux distribution between the facing-target. In this new facing-target sputtering system using only one cathode, we can expect the following features. (1) The magnetic flux distribution between the facing-target can be changed easily on the air side without breaking the vacuum, and electric discharge plasma between the facing-target is formed accordingly. (2) Low-damage and high-throughput plasma discharge are realized. (3) The new film deposition method provides high functionality and performance: the first layer is deposited in the low-damage plasma discharge, and the remaining layers are deposited in the high-throughput discharge, or the films are deposited in the magnetic flux distribution suited to the material. Furthermore, (4) we can expect applications in the fabrication of film-based electronic devices with multilayer film structures, making the sputtering system which combines magnetic flux distribution variable facing-target sputtering and the previously presented revolving facing-target sputtering.

Acknowledgement

Part of this study was made in Morohashi's laboratory, in the Graduate School of Science and Engineering, Yamaguchi University, as part of the Open Advanced Facilities Initiative for Innovation (Nanotechnology Network) of the Ministry of Education, Culture, Sports, Science and Technology. We deeply thank all members concerned.

References

[1] S. Morohashi, F. Shinoki, A. Shoji, M. Hayakawa and H. Hayakawa: Appl. Phys. Lett., 46, (1985) 1179.

Fig. 6 Deposition rate and substrate temperature as a function of the positions of the moving rod magnets for controlling the magnetic flux distribution variable facing-target sputtering process.
[2] S. Morohashi and S. Hasuo: *J. Appl. Phys.*, 61, (1987) 4835.
[3] F. Kessler, D. Herrmann and M. Powalla: *Thin Solid Films.*, 480 - 481, (2005) 491.
[4] S. Takasawa, S. Ukishima, N. Tani and S. Ishibashi: *ULVAC TECHNICAL JOURNAL*, 64, (2006) 18.
[5] S. Morohashi, M. Ikuta, T. Miyoshi, D. Matsumoto, S. Ariyoshi, M. Ukibe, M. Ohkubo and H. Matsuo: *IEEE Trans. Applied Superconductivity*, 15 (2005) 98.
[6] S. Ono and M. Naoe: *Suppl. Trans. JIM.*, 29 (1988) 57.
[7] JPN Patent, Pat. No. 3936970 (Inventor: Shinichi Morohashi, Yamaguchi University).
[8] S. Morohashi: *Shinku.*, 113 (2007) 14.
[9] "Development of a new low temperature sputtering system for organic electroluminescence electrodes and passivation films" (Principal investigator: Shinichi Morohashi, Yamaguchi University), Consortium R&D Project for Regional Revitalization (METI) 2005-2006.
[10] Two international patent applications, PCT/JP2008/058621 and PCT/JP2009/058976 (Inventor: Shinichi Morohashi, Yamaguchi University).
[11] S. Morohashi: *J. Vac. Soc. Jpn.*, 128 (2010) 26.
[12] Nikkan Kogyo Shimbun press release, Business & technology page, Nov. 12, 2010.
[13] S. Morohashi, Y. Matsumoto, K. Tanaka, K. Usui and E. Komatsu: *J. Vac. Soc. Jpn.*, 54 (2011) to be published.