Original Paper

Development of Biased Directional Sputtering(BDS) for Semiconductor Devices

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Abstract
This paper reports the Biased Directional Sputtering (BDS), which is a high directional sputtering technique using RF magnetron plasma and a substrate bias, for formation of barrier metals (Ti, TiN, Ta and TaN) for semiconductor devices. The RF magnetron plasma, which is denser than conventional DC magnetron plasma, ionizes sputtered metal atoms efficiently, and the substrate bias accelerates the ionized metal atoms perpendicularly to the substrate surface. Experimental results show that the plasma density of the BDS is higher than that of the conventional DC magnetron plasma. The ionization rate of the sputtered metal atoms reaches more than 90% at 13Pa. Consequently, excellent step coverage is obtained for high aspect ratio (AR) holes by the BDS deposition.

Key Words: High directionality, Ionized sputtering, Biased directional sputtering, RF magnetron plasma, Substrate bias

1. Introduction

Sputtering technique is now widely used in a metallization process of ultra-large-scale integrated circuits (ULSIs) [1]. In this process, barrier metals such as Ti, TiN, Ta and TaN must be deposited to high aspect ratio (AR) holes, that is, very deep and small diameter holes, with good step coverage (i.e. good bottom and side coverage) as shown in Figure 1(a). To obtain good step coverage, an incident angle on the substrate (indicated as θ in Figure 1) must be small. In another words, a directionality of sputtered metal atoms must be high, because poor directionality brings about poor step coverage as shown in Figure 1(b).

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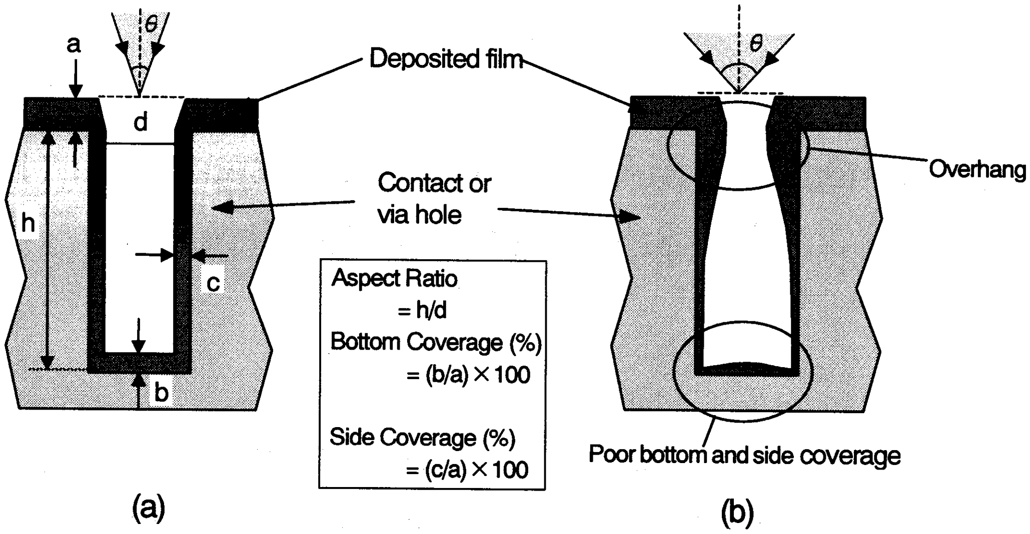


Figure. 1 Example of illustration showing good (conformal) and poor (overhanging) step coverage.
(a) Good (conformal) step coverage, (b) Poor (overhanging) step coverage.
Definition of aspect ratio, bottom coverage, and side coverage are shown above.

To overcome this problem, directional sputtering techniques, such as collimated sputtering [2] and low pressure long distance sputtering (LPLDS) techniques [3], have been developed. These techniques have been widely used in the metallization process for the formation of barrier metals such as Ti, TiN, Ta and TaN to via or contact holes [4].

The collimated sputtering uses a collimator located between the target and the substrate to enhance the directionality of the sputtered metal flux (Figure 2(a)). The part of the metal flux with large angular divergence is captured by the wall of the collimator hole and only the part of small angular divergence can pass through the collimator hole. Thus the collimator reduces an angular divergence of the sputtered metal flux.

The LPLDS deposition uses a long target to substrate (T/S) distance (25-30cm) and a low pressure condition (low 10^{-2}Pa). The long T/S distance results in reduction of the angular divergence of the depositing flux at the substrate, because the sputtered metal atoms with high incident angle are lost to the chamber wall. In addition, the low pressure reduces scattering of sputtered metal atoms by gas molecules and increases a mean free path for the sputtered metal atoms. Consequently, the directionality of the flux is enhanced (Figure 2(b)).

However, the collimated sputtering and the LPLDS technique become obsolete due to poor step coverage for high AR holes (AR>4.0). Further, the deposition profile in the hole, which is formed by the LPLDS, becomes asymmetric at the

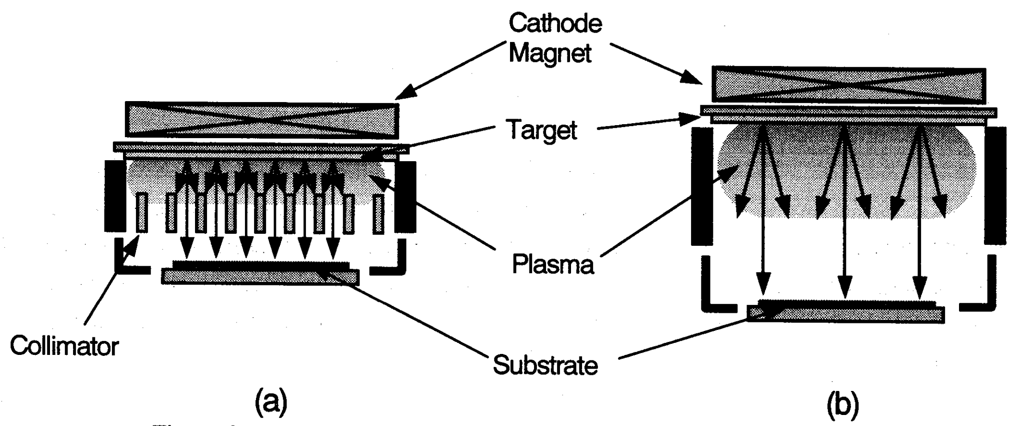


Figure. 2 Comparison of collimated sputtering and low pressure long distance sputtering (LPLDS) techniques.
(a) Collimated sputtering, (b) LPLDS.

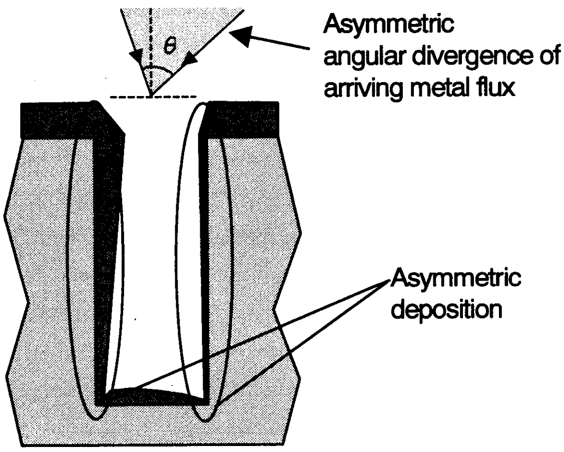


Figure. 3 Example of illustration showing asymmetric step coverage which is often seen in LPLDS deposition.

edge of the wafer (Figure 3). This asymmetry is due to asymmetric angular distribution of the arriving metal flux to the edge of the substrate [3].

Recently, an ionized sputtering technique, which yields better step coverage with high directionality of sputtered metal atoms, has attracted a considerable attention and several studies have been reported [5-8]. In the ionized sputtering technique, the sputtered metal atoms are ionized in the plasma and then, the ionized metal atoms are attracted to the negatively biased substrate. Thus the sputtered metal atoms reach the substrate with high directionality.

In this work, the biased directional sputtering (BDS) technique, which is the ionized sputtering using RF magnetron plasma and substrate bias, has been developed for metallization process for ULSIs under an intention to realize the high directional sputtering with simple configuration. Deposition characteristics of Ti, TiN, Ta and TaN films by means of BDS were investigated.

2. Development of BDS system

The BDS system was developed based on a conventional RF magnetron sputtering system. Schematic drawing of the BDS system is shown in Figure 4. This is a simple planar magnetron electrode system. This system has no coil antenna,

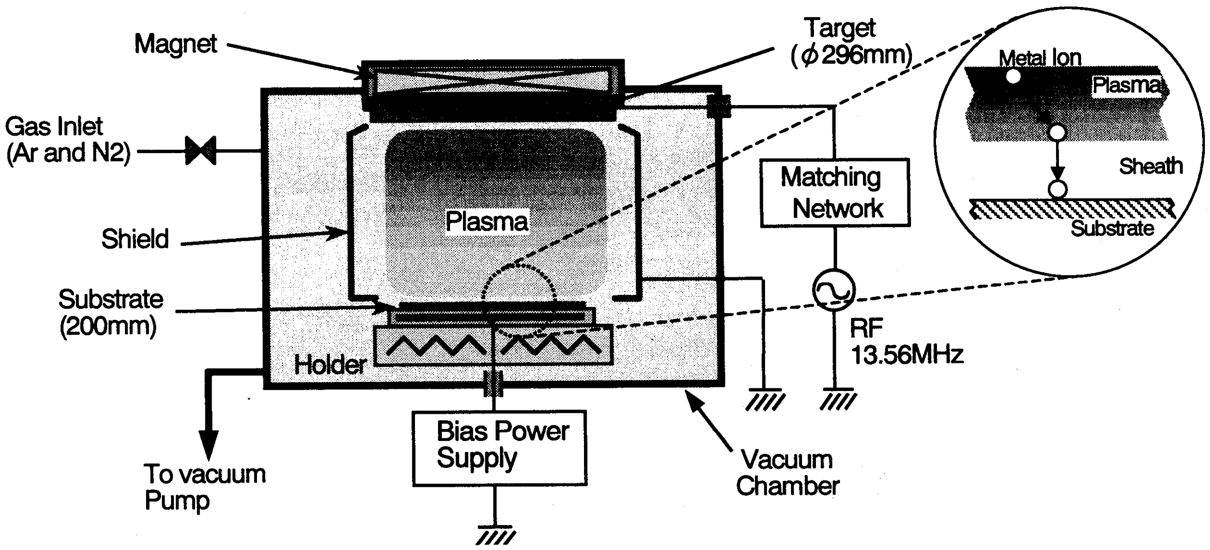


Figure. 4 Schematic drawing of BDS system.

which is used in another ionized sputtering system to promote the ionization of sputtered metal atoms [5-8]. 13.56 MHz RF power is applied to the target and the RF magnetron plasma is generated. The RF magnetron plasma yields denser plasma than that of the DC magnetron. The dense RF magnetron plasma serves both to sputter the target (Ti or Ta) and to ionize the sputtered metal atoms. The metal atoms are sputtered from the target and then ionized in the RF plasma.

On the other hand, RF or negative DC bias power is applied to the substrate during the deposition. The bias power develops negative bias potential on the substrate and the potential difference between the plasma and the substrate increases. Thus sheath electric field over the wafer surface increases compared with the field without the substrate bias. The ionized metal atoms incident to the sheath region are accelerated perpendicular to the substrate in the field. These metal ions are incident on the substrate surface with high directionality and then form the deposited film. Thus, excellent step coverage can be achieved. Further, cathode magnet arrangement was optimized to obtain good deposition uniformity and the shield shape was also designed to eliminate a spark discharge in the RF plasma. Base pressure of the process chamber is $<3x10^{-6}$Pa using a turbo molecular pump.

3. Plasma density and ionization rate measurements

3.1 Experimental setup for plasma measurements

To examine the plasma characteristics of the BDS system, plasma density and an ionization rate of the sputtered metal atoms were measured.

Plasma density of the BDS was measured using the Ta target. A Langmuir probe was used for this measurement. The Langmuir probe has structure to prevent a leakage current caused by the deposition to the probe (Figure. 5(a)).

The ionization rate of the sputtered metal was measured by means of a retarding potential method. Schematic diagram of the experimental apparatus is shown in Figure. 5(b). Bias voltage is applied to the second electrode to repel the ionized atoms and neutral atoms can pass through the second electrode. Thus the ionization rate can be obtained as a difference of the deposited film weight between with and without the bias voltage.

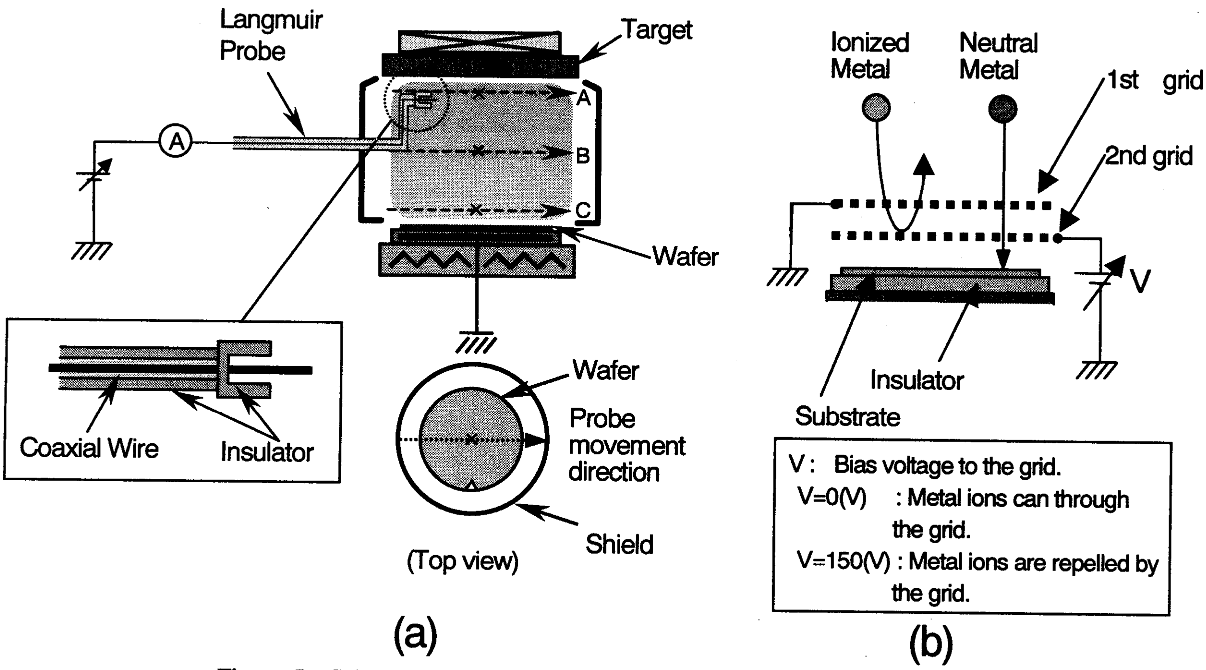
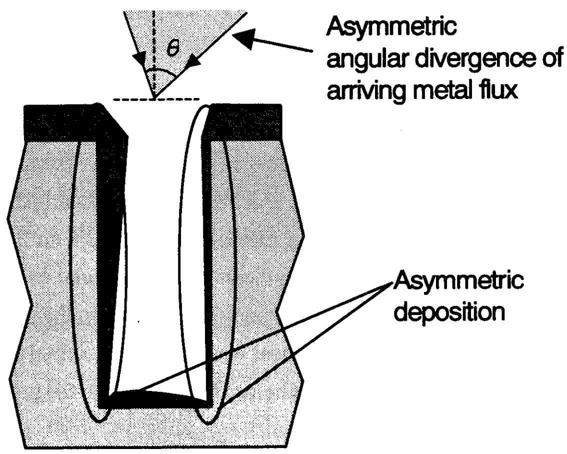


Figure. 5 Schematic drawing of equipment for plasma density and ionization measurements used in this study.
(a) Plasma density measurement (Langmuir probe) system,
(b) Ionization rate measurement system.



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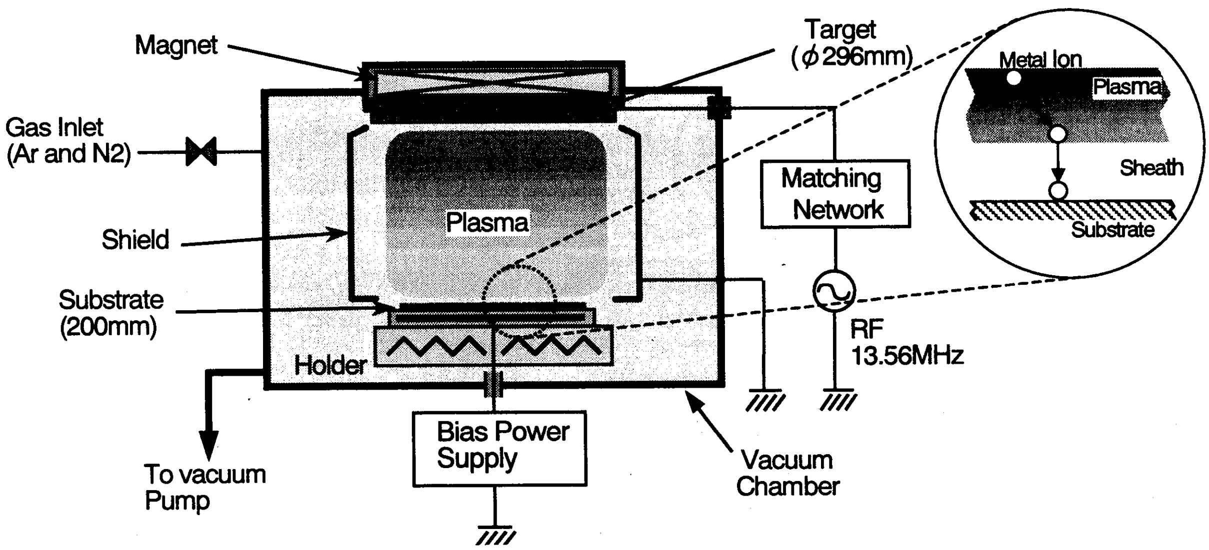

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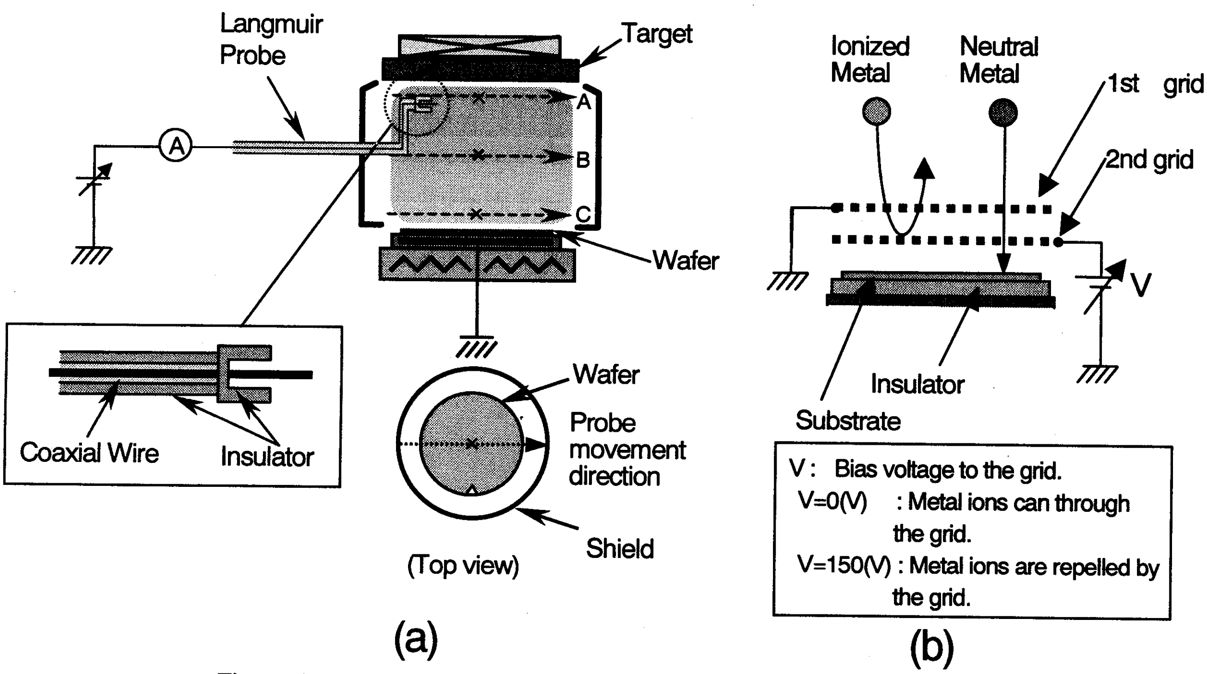

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3.2 Plasma density in BDS

Figure 6 shows the ion density in the BDS plasma. The density is about $1x10^{12}cm^{-3}$ at the position of 10mm from the target. This density is higher than that of the conventional DC magnetron sputtering ($\sim 10^{9}cm^{-3}$). The ion density is almost the same between the position A (10mm from the target) and B (60mm from the target), but decreases to $6x10^{10}cm^{-3}$ at the position C (113mm from the target). This result indicates that the high density region exists in the upper half region of the plasma. The distribution of the ion density in the radial direction is influenced by the magnetic field of the cathode magnet placed to the backside of the target, while uniform density distribution is obtained above the substrate.

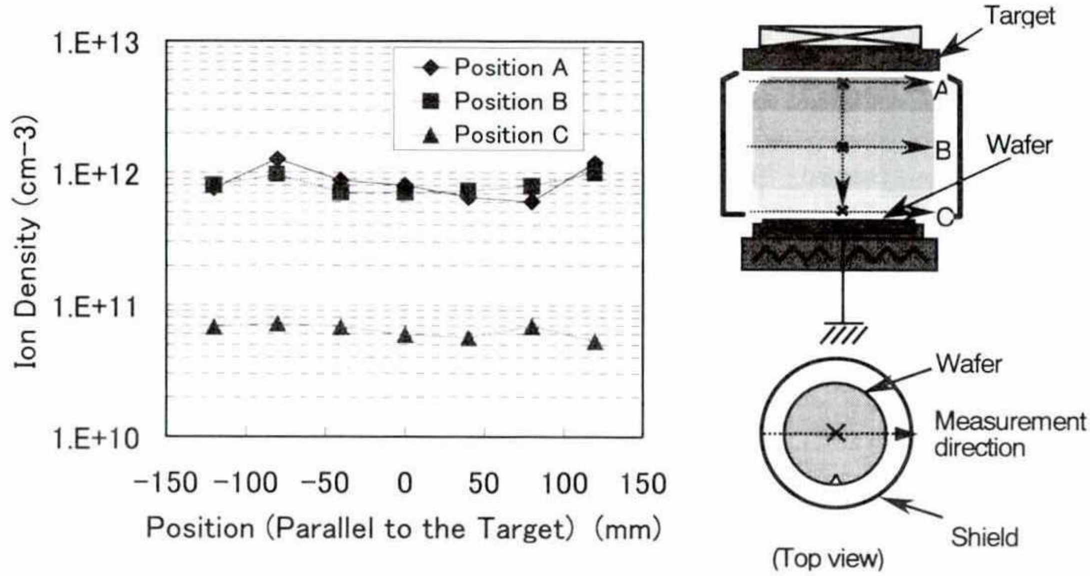


Figure. 6 Plasma ion density in the BDS plasma.
Position A: 10mm beneath the target, Position B: 60mm from the target,
Position C: 120mm under the target.

3.3 Ionization rate in the BDS plasma

Figure 7 shows the ionization rate of the sputtered tantalum atoms as a function of Ar pressure. The ionization rate greatly depends on the pressure. The ionization rate is 2-3% at 2Pa. This ionization rate increases with increasing the pressure, and reaches more than 90% at 13Pa. This result shows that very high ionization rate is achieved at the pressure range of 10. 20Pa, which is typically used for the BDS deposition.

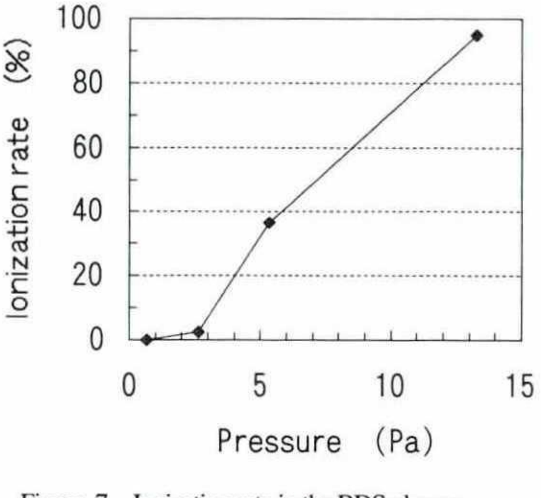


Figure. 7 Ionization rate in the BDS plasma.
Ta target was used for the measurement.

4. Deposition characteristics

4.1 Conditions for deposition

The step coverages, deposition rates and a film resistivity by the BDS deposition were examined for Ti, TiN, Ta and TaN.

Conditions for depositions demonstrated in this report are summarized in Table I. These parameters were chosen to obtain desirable film characteristics as the barrier film. The RF power was varied over the range from 3.0 to 8.0 kW. The DC bias power applied to substrate holder was 250W. The pressure range from 9 to 17Pa was used for the deposition. The target-substrate (T/S) distance was optimized for each deposition metal at the range from 90 to 130mm. 200mm diameter Si wafers with contact hole pattern were used as substrates for the depositions. Deposition temperature was 350°C for Ti and TiN, and 200°C for Ta and TaN.

Depositions were done on silicon wafers with contact hole patterns. After the deposition, the cross section of the contact holes were observed by Scanning Electron Microscope (SEM) and the step coverages (i.e. the bottom ant side coverages) of the deposited films were examind. The resistivities of the films were measured by means of a four-point probe method.

Table 1: Conditions for depositions

Parameters		Ti	TiN	Ta	TaN
T/S *distance	(mm)	120	120	120	120
Pressure	(Pa)	10.6	9.3	17.0	17.0
RF power	(kW)	5.5	8.0	3.0	3.6
Wafer temperature	(°C)	350	350	200	R.T.
Bias power	(W)	0-250	0-250	0	0
N2 flow ratio**	(%)	0	12	0	4

* Target/Substrate

** (N_2 flow ratio (%))=(N_2 flow(sccm)) / (Total gas flow(sccm))× 100

4.2 Deposition characteristics of Ti and TiN

Figure 8 shows dependence of bottom coverage on the aspect ratio of a contact hole in Ti. Bottom coverage of 23% is obtained for the 6.0 aspect ratio hole. The coverage is improved when the bias voltage is applied to the substrate. The bottom coverage increases up to 38% for 6.0 aspect ratio.

Figure 9 shows dependence of bottom coverage on the aspect ratio of the contact hole for TiN. The bottom coverage of 27% is obtained for the 6.0 aspect ratio hole. The bottom coverage is also improved to 38% for the 6.0 aspect ratio hole by applying the bias to the substrate. The deposition profile in the contact hole at the both center and edge of the wafer is symmetrical as well as Ti. The deposition rates are 40nm/min for Ti and 20nm/min for TiN. Further, the resistivity of Ti and TiN films are less than 100 $\mu\Omega\cdot$cm.

4.3 Deposition characteristics of Ta and TaN

Dependence of coverage on the aspect ratio of a contact hole in Ta and TaN are shown in Figure 10 and 11, respectively. The bottom coverages are about 40% (AR=5.0) for Ta and 30% (AR=5.0) for TaN. For both films, the side coverage is about 10% (AR=5.0).

The deposition rates are 30nm/min for Ta and 50nm/min for TaN. There is no difference in the shape between the contact hole at the center and that at the edge as well as Ti and TiN. The resistivity is less than 300 $\mu\Omega\cdot$cm for Ta and TaN.

4.4 Symmetry of deposition profile in hole

Figure 12 is cross sectional SEM images showing the profile of the Ti deposition with substrate bias in the holes. The deposition profile shows that there is no difference in the shape between the hole at the center and that at the edge on the wafer. The deposition profile shows good symmetry at the both positions on the wafer. Asymmetric deposition profile, which is often observed in the LPLDS deposition, is not observed in the BDS deposition.

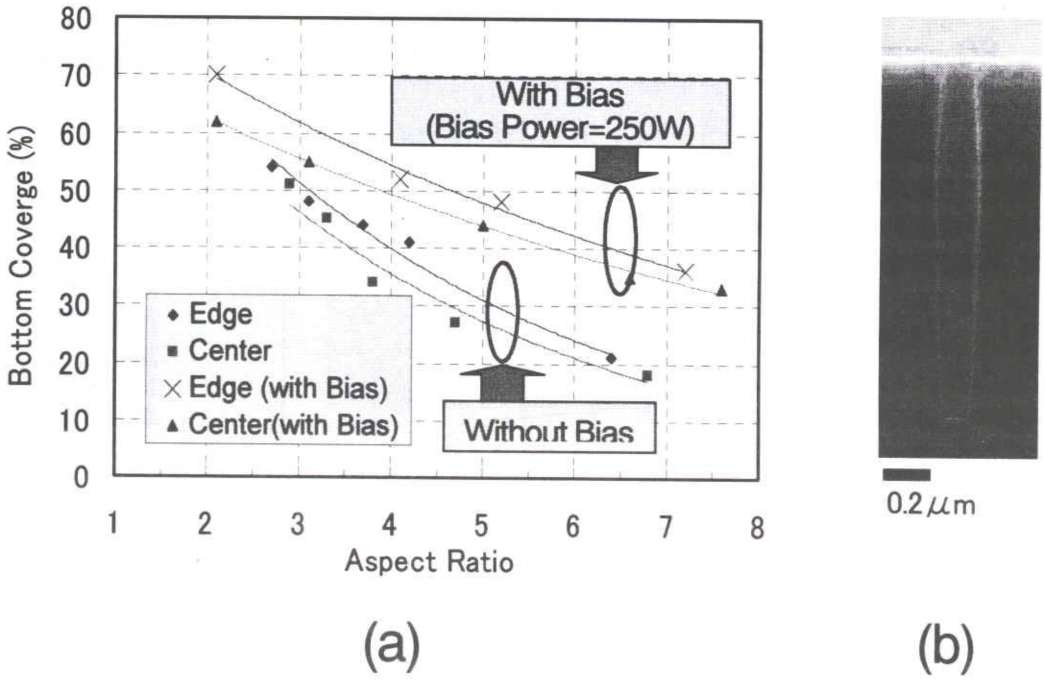


Figure. 8 Coverages of Ti.
(a) Aspect ratio vs.bottom coverage, (b) SEM photograph of TiN deposited at the center of wafer (bias power is 250W). Aspect ratio is 7.6.

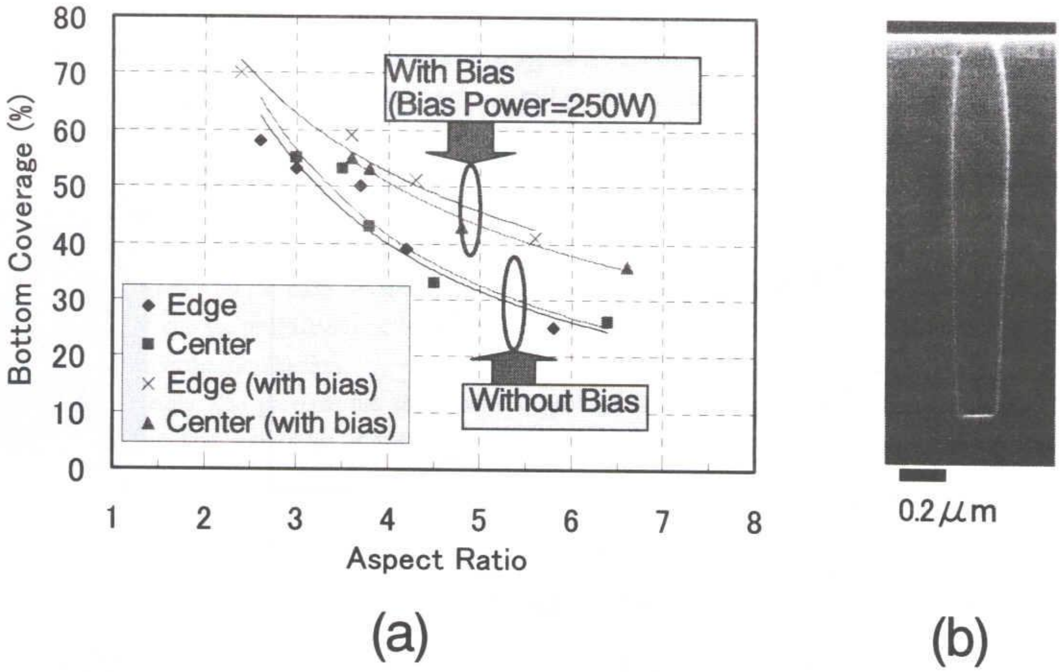
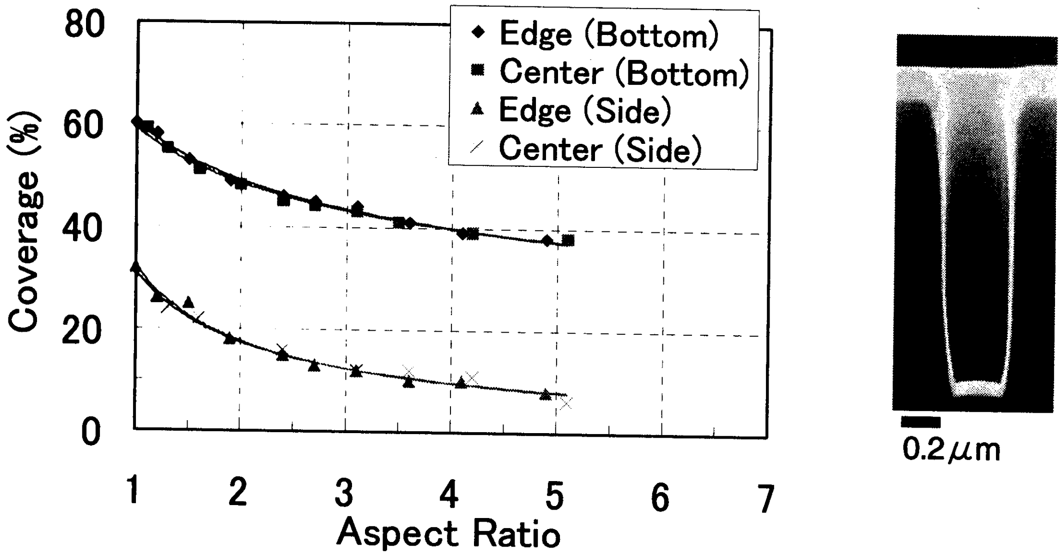
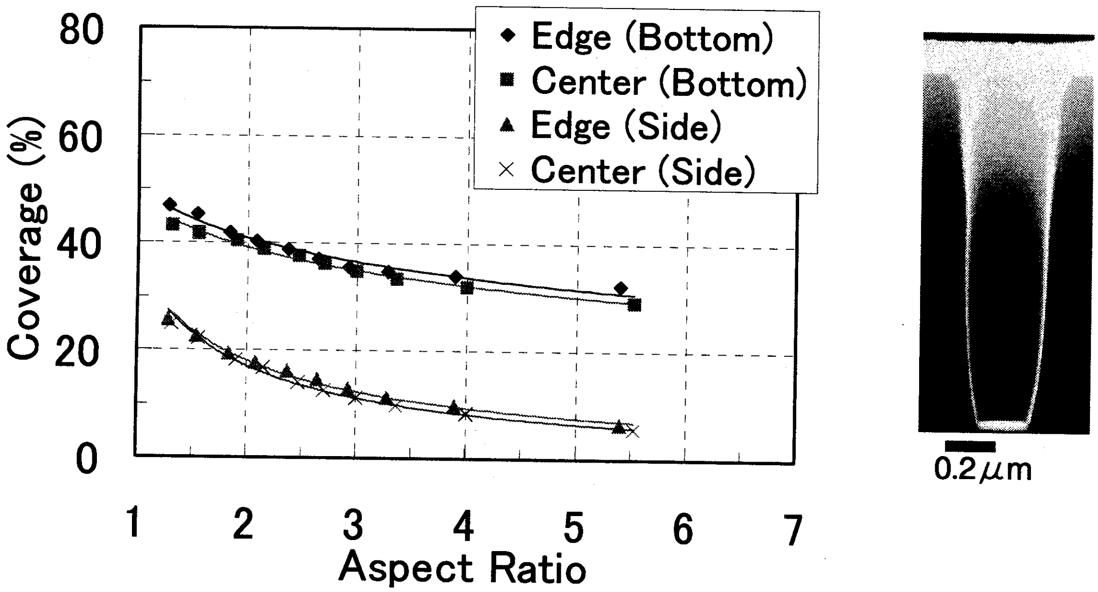


Figure. 9 Coverages of TiN.
(a) Aspect ratio vs.bottom coverage, (b) SEM photograph of TiN deposited at the center of wafer (bias power is 250W). Aspect ratio is 6.6.



(a) (b)

Figure. 10 Coverages of Ta.
(a) Aspect ratio vs.bottom coverage (bottom and side),
(b) SEM photograph of Ta deposited at the center of wafer.
Aspect ratio is 3.5.



(a) (b)

Figure. 11 Coverages of TaN.
(a) Aspect ratio vs. bottom coverage (bottom and side),
(b) SEM photograph of TaN deposited at the center of wafer.
Aspect ratio is 3.3.

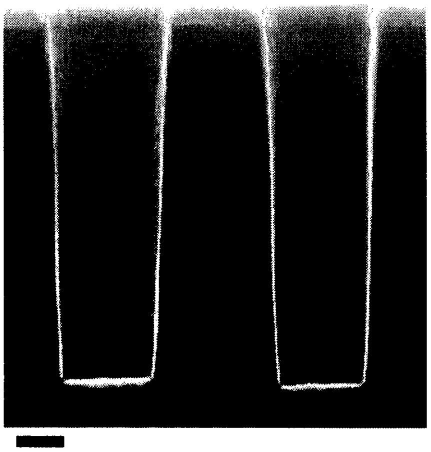


Figure. 12 Comparison of deposition profile observed at the center and at the edge of wafer. Deposition was done with applying 250W of the substrate bias.

5. Discussion

5.1 Plasma density and ionization rate

The high density in the BDS plasma is attributed to the adoption of the RF (13.56MHz). In general, plasma density becomes higher as the discharge frequency becomes higher [9]. This means that we can expect that much higher density can be obtained by using higher frequency than 13.56MHz.

The ionization rate strongly depends on the pressure. This result indicates that the high ionization rate of the sputtered metal atoms is due to the high pressure condition used in the BDS plasma. In the high pressure condition, the mean free path becomes short. In this condition, a residential time of the sputtered atoms in the plasma becomes longer. As a result, sputtered metal atoms can be ionized efficiently in the high density BDS plasma.

5.2 Step coverages and symmetry of deposition profile

The good step coverages by the BDS are attained by the improvement of directionality of the sputtered atoms. The good directionality prevents the overhanging at the top of holes and enables to reaches the sputtered atoms to the bottom of the deep hole as shown in the introduction.

The good directionality also prevents the asymmetric deposition profile, which is often observed for the LPLDS deposition, in the contact hole at the edge of wafer. The mechanism of the improvement of the deposition profile can be explained by an illustration in Figure 13.

In this figure, a comparison between the LPLDS and the BDS is shown. The asymmetry of the deposition profile in the contact hole at the edge of the wafer, which is often observed in the LPLDS, is caused by asymmetric angular distribution of the arriving metal flux to the substrate (Figure 13(a)). The center region of the substrate receives the sputtered metal flux with symmetric angular distribution (i.e.,$\theta_r = \theta_l$ in Figure 13(a)). Consequently, the symmetric deposition profile is obtained. However, the edge region of the substrate receives more sputtered flux from the center than from the edge of the target (i.e., $\theta_r > \theta_l$) due to the limitation of the target size. This result in the thick deposition on inward-facing wall of the hole at the edge of the substrate compared with outward-facing wall as shown in Figure 13(a).

As regards the BDS, the operating pressure is 10-20Pa, which is higher than that of LPLDS (low 10^{-2}Pa). Under the pressure condition, the mean free path is less than 1mm and those metal atoms collide with another atoms several tenth times before reaching to the wafer. As a result, the sputtered metal atoms arriving at the sheath on the substrate has random incident angles. Thus the angular distribution of the arriving sputtered metal flux is independent of the position on the substrate and is symmetric about the surface normal both on the center and on the edge of the substrate (Figure 13(b)). The sputtered metal atoms ionized in the RF plasma are accelerated across the sheath at normal incidence with little angular divergence. Thus the metal film can be deposited at the bottom of deep hole. Consequently, excellent step coverage and asymmetric deposition profile is obtained.

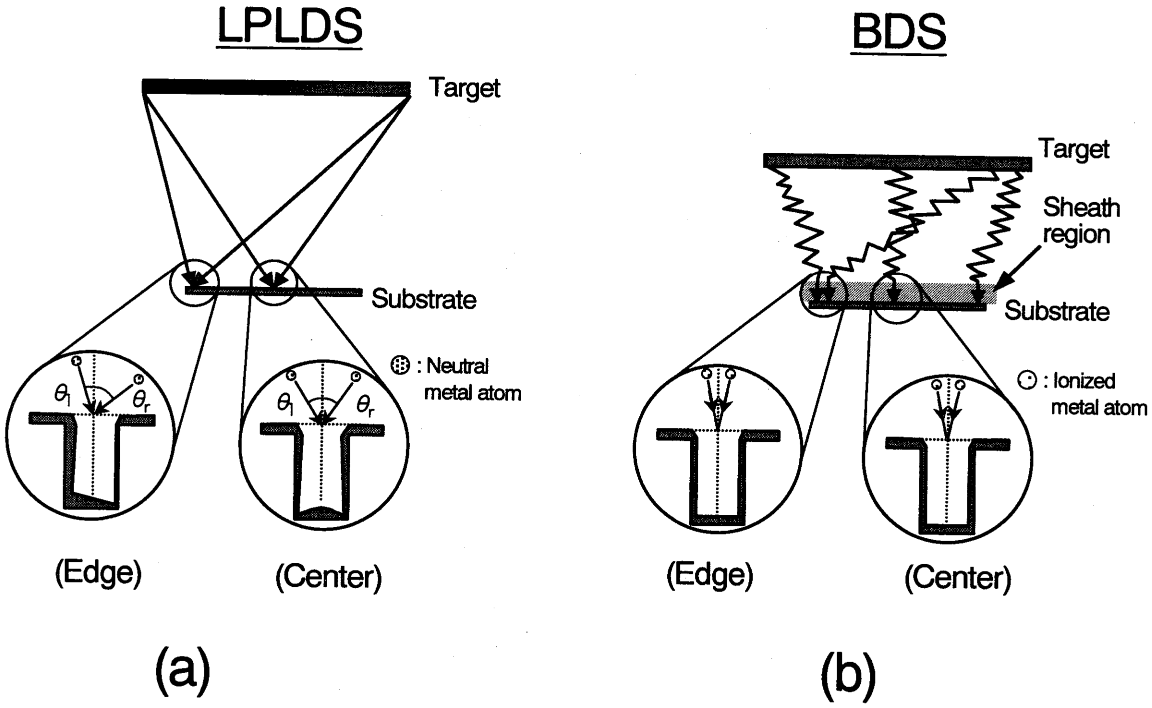


Figure. 13 Illustration which explains the improvement mechanism of the deposition profile by the BDS.

6. Conclusion

The BDS technique, which aims at the formation of the barrier metals for the high aspect ratio holes, has been developed. The plasma density is about $1x10^{12}cm^{-3}$, which is denser than the conventional DC magnetron plasma. The ionization rate of the sputtered metal atoms reaches to 90% at 13Pa for Ta target. The optimizations of deposition condition led to the improvement of the step coverage and the asymmetry of the deposition profile compared with other conventional techniques. The coverage is about 40% (AR=6.0) for Ti and TiN, 40% (AR=5.0) for Ta and 30% (AR=5.0) for TaN.

These results indicate that the BDS technique is a promising technology for the future ULSIs fabrication.

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