Extended Abstracts of the 2000 International Conference on Solid State Devices and Materials, Sendai, 2000, pp. 36–37

A-2-5

Dielectric Breakdown and Light Emission in Copper Damascene Structure under Bias-Temperature Stress

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1. Introduction

Copper (Cu) is suitable for ULSI interconnect material because of its lower electrical resistivity and of higher stress/electro-migration resistance. Some reliability issues however remain to be resolved. One major problem is time-dependent dielectric breakdown (TDDB) induced by Cu-ion drift. Plasma-enhanced CVD silicon oxide (p-SiO) film could not provide 10-years reliability against dielectric breakdown under operating conditions [1,2]. To solve this problem, it is necessary to cover the entire Cu surface both with metallic and with insulator barrier. We reported the combination of TiN and plasma-enhanced CVD silicon nitride (p-SiN) can provide sufficient reliability against TDDB degradation [2,3]. In recent report [4], however, we found surface treatments after Cu-CMP greatly influence TDDB lifetime and electrical leakage of Cu damascene interconnect.

In this paper, we investigate relationship between TDDB lifetime and electrical leakage of damascene Cu comb-type capacitors. The charge to breakdown, which is the amount of the line-to-line leakage current to dielectric breakdown, strongly correlates with TDDB lifetime. Visible light emission was observed in stressed capacitors. From the spectrum analysis, intralevel leakage mechanism is also discussed.

2. Experimental

TDDB lifetimes and the line-to-line leakages were measured at 140°C using comb-type capacitors as illustrated in Fig. 1(a). Cu and TiN were embedded in trenches with equal width and spacing of 0.5 μm (Fig. 1(b)). After CMP process, various kinds of surface treatment, such as wet cleaning and plasma exposure, were carried out prior to depositing p-SiN capping layer [4]. In these pre-treatments, only NH_3 plasma treatment successfully improves TDDB lifetime and leakage current [4]. So this paper mainly focuses on the effect of NH_3 plasma treatment.

Light emissions from the stressed capacitors were collected and analyzed by hot-electron analyzer (Hamamatsu PHEMOS 200) with band-pass filters (400 – 1100 nm).

3. Results and Discussions

Fig. 2 shows the effect of NH_3 plasma treatment on TDDB lifetime (τ_{BD}) of the capacitors. NH_3 plasma treatment improves τ_{BD} about 7 orders of magnitude. As the influence of NH_3 plasma treatment is only limited to the CMP surface region (< 10 nm) [2], the differences in τ_{BD} in Fig. 2 are attributed to the differences in capping p-SiN/Cu CMP interface conditions. Cross-sectional SEM photograph of Cu comb-type capacitor after TDDB test also indicates that dielectric breakdown occurred in the vicinity of capping p-SiN layer (Fig. 3).

Fig. 4 shows *j*-*E* characteristics of Cu comb-type capacitors with and without NH_3 plasma treatment. NH_3 plasma treatment does not only decrease line-to-line leakage current but also improves breakdown field strength about twice. The leakage current with NH_3 plasma treatment, however, is much higher than p-SiO bulk leakage current. As reported by Loke *et al.* [5], the planarized surface (capping p-SiN/p-SiO interface in this case) is dominant leakage path in damascene interconnect. Therefore, we suspect that dielectric breakdown in damascene interconnect is responsible for enormous electron conduction along p-SiN/p-SiO interface.

In order to clarify the relationship between TDDB lifetime and leakage current, we employ the charge to breakdown (Q_{BD}) analysis that is common method in gate oxide reliability evaluation [6]. Q_{BD} is calculated by integrating line-to-line leakage current from t=5 sec (initial sampling time) to $t=\tau_{BD}$. As shown in Fig. 5, Q_{BD} versus τ_{BD} plot exhibits universal straight line, independent of with or without NH_3 plasma treatment. This result suggests electron amount through the capacitor strongly correlates to TDDB lifetime. Fig. 5 also includes τ_{BD}-Q_{BD} characteristics of planar MIS and MIM capacitors. For planar capacitors, no universal relationship between Q_{BD} and τ_{BD} was observed. This result is natural because TDDB lifetime of planar capacitors is determined by amount of Cu-ions injected to insulator film [2].

Light emission analysis of stressed Cu comb-type capacitor was performed to identify the leakage current conduction mechanism. Visible light emission was observed from the overall area of stressed capacitor (Fig. 6(a)) and emission points are insulator region between adjacent Cu lines (Fig. 6(b)). Leakage current dependence of emission intensity at each field strength (E_f) is shown in Fig. 7. Linear relationship between emission intensity and leakage current was observed for both capacitors. From photon energy spectrum (Fig. 8), photon emission with wide range of energy was observed. Moreover, intensities of high-energy photon (>2 eV) are high at high stress field though intensities of low-energy (<2 eV) are high at low stress field (so-called *Blue shift*). As SiN, as well as SiO, has wide energy gap (>5 eV), no visible light emission occurs in these materials. Therefore, these photon emission phenomena are attributed to Cu damascene structure. These emission characteristics (Fig. 7 and Fig. 8) are very similar to those of injection electroluminescence that is recombination radiation of high-energy electrons excited by applied electric field [7]. This process could occur via radiative transition between energy states generated by impurities and/or defects at p-SiN/p-SiO interface. We believe that dielectric breakdown in Cu damascene capacitor is induced by large amount of high-energy electrons conducting through p-SiN/p-SiO interface. TDDB reliability improvement by NH_3 plasma treatment would be achieved by decreasing impurity and defect density on Cu CMP surface [4].

4. Conclusions

TDDB lifetime of damascene Cu comb-type capacitor strongly correlates to the amount of the line-to-line leakage current to dielectric breakdown. Photon emission from stressed damascene capacitors can be explained by injection electroluminescence mechanism. Large amounts of high-energy electrons conducting through p-SiN/p-SiO interface cause photon emission and dielectric breakdown.

5. References

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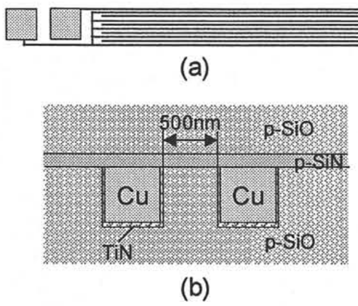

Fig. 1 (a) Plan view schematic and (b) Cross sectional schematic of TDDB test structure.

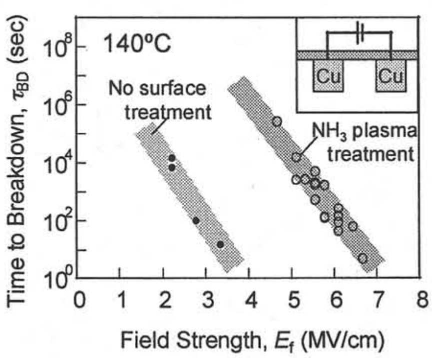

Fig.2 TDDB lifetime of Cu-comb capacitors with and without NH_3 plasma treatment.

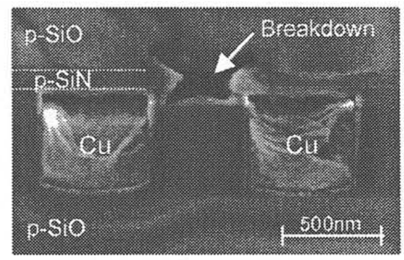

Fig.3 Cross-sectional SEM photograph of Cu Comb-capacitor after breakdown.

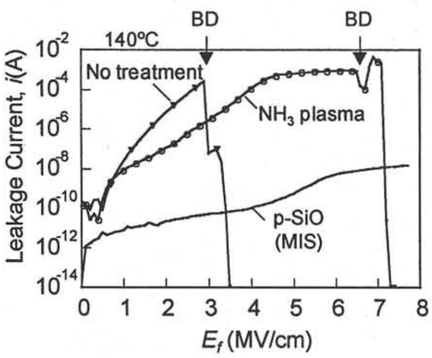

Fig. 4 Typical j-E characteristics of Cu comb-type capacitors with and without NH_3 plasma treatment.

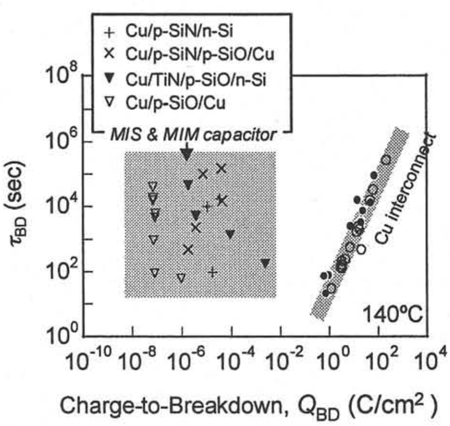

Fig. 5 Q_{BD} versus τ_{BD} characteristics of Cu interconnect and MIS/MIM capacitors. (○:with NH_3 plasma and ●:w/o NH_3 plasma)

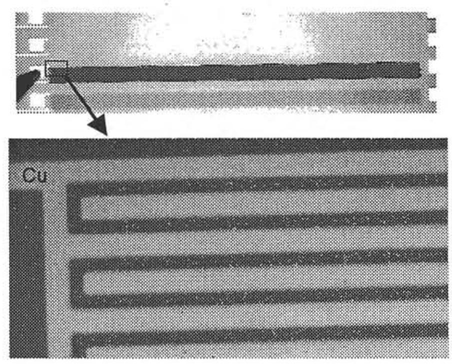

Fig. 6 Micrograph of the photon emission from Cu comb-type capacitor.
(a) Low and (b) high magnification view
Bright point is emission point.

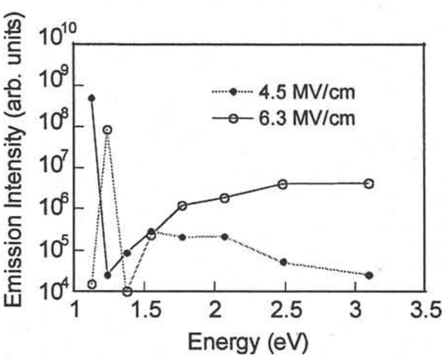

Fig. 7 Energy spectra of photon emission at each field strength.

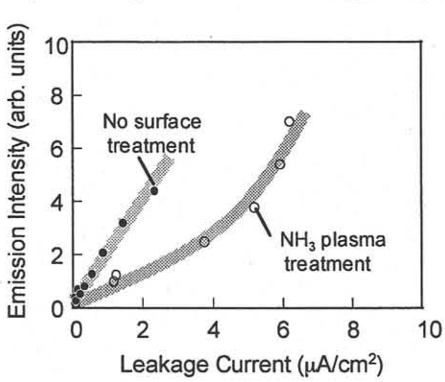

Fig. 8 Leakage current dependence of emission intensity with and without NH_3 plasma treatment.