Abstract—We investigated characteristics impact of alpha-particles irradiation to power MOSFETs and demonstrated alpha-particle shielding effect of thick copper plating film on a power MOSFET die. Irradiation under gate-source bias caused threshold voltage (Vth) decrease due to generated trapped holes in gate oxide, however, no Vth shift occurred under drain–source bias. We found that sensitivity to alpha-particles depends on gate structures of trench or planar. Recovery behavior of Vth shift by gate bias or thermal annealing support the hole trapping model in the gate oxide. We evaluated alpha-particle shielding effect of thick copper plating film. We demonstrated more than 15 micrometer thick copper plating on the power MOSFET shielded alpha-particles successfully.

Keywords—alpha-particle, power MOSFET, copper plating film, threshold voltage shift, hole trapping

I. INTRODUCTION

Continuous cell pitch shrinking of trench power MOSFET has achieved significant chip On-resistance reduction in last three decades [1], [2]. Furthermore, charge coupling technologies such as superjunction [3] and trench Field Plate (FP) MOSFET [4] drastically reduced drift layer resistance and overcame silicon limit. In addition, copper clip source connection technology decreased parasitic package resistance [5], which is especially important for low voltage devices. These technologies enabled us to realize extremely low on-resistance power MOSFET.

Recently, threshold voltage (Vth) shift of power MOSFET due to alpha-particles which radiated from the lead solder of copper clip was reported [6]. The mechanism of the Vth shift is illustrated in Fig. 1 and 2. The lead solder on the source metal slightly radiates alpha-particles because the lead solder contains small amount of radioactive elements such as lead-210 (210Pb) which become polonium-210 (210Po) alpha-source [7]. These alpha-particles penetrates gate oxide in some probability and generates electron-hole pairs. Compare to electron, field effect mobility of hole is estimated to be very low [8]. Therefore, when the gate is biased, electrons are swept out and holes are left behind and gradually trapped in the gate oxide. These trapped holes in the gate oxide decrease Vth.

Historically, the effect of alpha-particles to semiconductor devices was recognized as one of the cause of "soft error" in dynamic memory devices at the end of the 1970s [9]. In this case, the main source of the alpha-particles was identified as radioactive decay of uranium and thorium in packaging material. In addition, it is reported that the sensitivity of the alpha-particles (error rate) increase as increasing density of memory cells. Considering analogy with memory devices, as the density of the cell increase in power MOSFET, the impact of alpha-particle become remarkable as well.

The practical influence of the Vth shift of power MOSFET by alpha-particles was also investigated in [6]. In fact, no significant difference was observed in TDBB, avalanche capability and Safe Operating Area (SOA). These results are because holes are trapped in very small region in active area and impact is limited to sub-threshold characteristics degradation. In addition, the Vth shift recovery by positive gate bias was also reported [6]. However, avoiding these alpha-particles effects is more desirable. One solution is using low-alpha (low alpha-particle emission) solder which is proposed in [6]. The other solution we propose is shielding alpha-particles. As well known, alpha-particles are very interactive with substances, therefore, shielding alpha-particles is relatively easy, for instance by using a paper.

In this article, we used thick copper (Cu) plating film on the power MOSFET [10] for shielding alpha-particles and demonstrated its effect.

Fig. 1. A power MOSFET die mounted on copper clip package. Alpha-particles radiated from lead solder on the source metal penetrate the power MOSFET die.

Fig. 2. Vth shift model of alpha-particle irradiation under positive or negative gate bias. Incident alpha-particles to gate oxide generates electron-hole pairs. Holes separated from electron due to gate electric field are trapped in the gate oxide.
II. EXPERIMENTAL METHOD

In order to investigate behavior to alpha-particle penetration, we irradiated alpha-particles to a bare power MOSFET die by using an americium-241(241Am) artificial alpha-source as shown in Fig. 3. The energy of alpha-particles emitted from 241Am is about 5.5MeV. This energy is almost the same as alpha-particles energy of 5.3MeV from 210Po in lead solder. The radioactivity of exploited 241Am alpha-source was 40kBq, which approximately corresponded to 1.4x10^8 counts / hour cm². The tested power MOSFET die was mounted on Direct Bonding Copper (DBC) substrate as illustrated in Fig. 3(b). During alpha-irradiation, gate–source was biased with positive or negative DC voltage and drain-source was shorted. Besides, irradiation under drain–source reverse bias without gate bias was tested. We mainly evaluated trench FP MOSFETs. In addition, for investigating alpha-particle sensitivity dependence on gate structures, we evaluated planar gate power MOSFETs for comparison. In order to reveal trapped hole state, we studied recovery behavior of Vth by thermal annealing or gate bias. After these comprehensive studies of device behavior, we evaluated alpha-particle shielding effect of thick copper plating film on the surface of the trench FP MOSFET. We fabricated 5 to 20μm Cu plated samples and irradiated alpha-particles to these surface, then evaluated degree of Vth shift under gate bias.

III. RESULTS AND DISCUSSION

A. Alpha-particle irradiation with gate bias

We irradiated alpha-particles to trench FP MOSFET under gate bias. Fig. 4 shows gate voltage (V_G) – drain current density (J_D) characteristics of before and after alpha-particle irradiation. Shoulder like shape due to negative Vth shift in low current regime was observed both positive and negative gate bias, however no significant Vth shift was observed without gate bias. These results supported the model of electron-hole separation and hole trapping due to gate electric field as illustrated in Fig. 2.

The shoulder like shape of V_G-J_D curve suggested localized current leakage resulted from local Vth decrease. Fig. 5 shows photo emission analysis of drain current leak points. Each leak spots in active area implies random incidence of alpha-particles.

We also checked impact of alpha-irradiation under drain-source reverse bias. In contrast with the gate bias case, no significant change was observed both V_G-J_D and drain voltage (V_D) –J_D characteristics as shown in Fig. 6. As previously stated, alpha-particles generate electron-hole pairs in the device. In the case of drain-source bias, generation of trapped holes in the oxide is negligible because electric field in the gate oxide is very low. Instead, electron-hole pairs in depleted layer might be spatially separated by drain-source electric field. However, these carriers are swept out quickly by drain-source electric field.
B. Alpha-particle sensitivity of different gate structures

Sensitivity of alpha-particle should depend on the gate structure because the Vth shift is caused by alpha-particle penetration to the gate oxide. We compared alpha-particle irradiation behavior of different gate structure: trench gate and planar gate as shown in Fig. 7. In the case of the trench gate, Vth shifted immediately after 10 seconds irradiation, however, in the case of the planar structure, no characteristics change was observed even at 100 seconds irradiation. We considered that this sensitivity difference comes from incident angle of alpha-particles to the channel as illustrated in Fig. 7. In the case of the trench gate, the incident alpha-particles in parallel to the channel create hole trapped region throughout the channel, which leads channel leakage. In contrast, in the case of the planar gate, incident alpha-particles in perpendicular to the channel partially create hole trapped region in channel; thus no Vth shift occurs. Similar results and a model were also reported in heavy ion irradiation to trench power MOSFET [11].

C. Vth shift recovery behavior

In order to investigate trapped hole state in the gate oxide, we estimated Vth shift recovery with thermal annealing and gate bias. We prepared Vth shifted samples by alpha-particles irradiation with positive gate bias for examining Vth recovery behavior. Vth shift recovered gradually by annealing. From Arrhenius plot shown in Fig. 8, we obtained activation energy of the Vth recovery of 0.47eV, which correspond to trapping energy of the holes. Furthermore, the Vth shift recovered by gate bias as shown in Fig. 9. The recovery under positive gate bias started over +4.0MV/cm and became obvious in +6.0MV/cm. This result agreed with previous report [6]. Compare to positive gate bias case, the recovery under negative gate bias is slow in the same electric field of 6.0MV/cm. This is explained by different behavior of trapped holes near the channel in each gate bias direction as depicted in Fig. 10.

D. Alpha-particle shield effect of thick Cu plating film

After the comprehensive study of the alpha-irradiated power MOSFET behavior, we evaluated alpha-particle shielding effect of thick copper plating film on the trench FP MOSFET. We calculated penetration depth of 5.5MeV alpha-particles from $^{241}$Am into Cu, aluminum (Al) and silicon (Si) using NIST standard reference database [12]. The penetration depth of 5.5MeV alpha-particle into Cu was calculated as 11.8 $\mu$m as plotted in Fig. 11. As this calculation indicated, Cu is suitable material for shielding alpha-particle because the density of Cu is higher than typical source metal of Al. Therefore, we expected that over 11.8$\mu$m thick Cu film on the device is capable of shielding alpha-particles as illustrated in Fig. 12. In order to evaluate shielding effect of copper film, we fabricated 5, 10, 15 and 20$\mu$m thick Cu plated trench FP MOSFET samples. As shown in Fig. 13, 5$\mu$m thick Cu plating sample showed Vth shift as well as conventional sample in Fig. 4; and 10$\mu$m thick Cu plating sample showed slight Vth shift. In contrast, no Vth degradation was observed.
in 15 and 20 μm thick Cu plating samples. These results are reasonable for the alpha-particle penetration depth of 11.8μm. This results also indicated more than 15μm is enough Cu thickness for shielding 5.3MeV alpha-particles radiated from 210Po in lead solder. Furthermore, the possible maximum reasonable for the alpha-particle penetration depth of 11.8μm is 15 and 20 μm. This results also indicated more than 15 μm is enough Cu thickness for shielding 5.3MeV alpha-particles radiated from 210Po in lead solder. Furthermore, the possible maximum alpha-particle energy is 8.78MeV (212Po) in thorium decay chain [13]; thus maximum penetration depth in Cu is estimated to 23μm. Therefore, more than 23 μm thick Cu plating film must completely shield alpha-particles.

**Fig. 11.** Calculated penetration depth of Alpha-particle into copper (Cu), aluminum (Al) and silicon (Si). The penetration depth of 5.5MeV alpha-particles into Cu was calculated as 11.8μm.

**Fig. 12.** The concept of alpha-particle shielding by thick copper plating film on the device. Copper plating film thicker than alpha-particle penetration depth is expected to shield alpha-particles.

**Fig. 13.** Cu plating thickness dependence of alpha-particle shielding effect. These results indicated that 15 and 20 μm thick copper suppressed penetration of 5.5MeV alpha-particles to the gate oxide. These are reasonable results for alpha-particles penetration depth of 11.8μm.

**IV. CONCLUSIONS**

We investigated Vth shift phenomena of power MOSFET by alpha-particles irradiation using 241Am alpha-source. Incident alpha-particles to gate oxide create electron-hole pairs. Under gate bias condition, spatially separated holes trapped in the gate oxide and these holes decrease Vth. The study of Vth recovery behavior by annealing and gate bias supports this degradation model. The sensitivity of Vth degradation to alpha-particle incidence depends on gate structures. Compare to planar gate structure, trench gate structure is more sensitive due to alpha-particles penetration in parallel to the channel. In order to avoid subthreshold characteristics degradation by alpha-particles, we proposed shielding alpha-particles by thick Cu plating films on the devices. We demonstrated more than 15μm thick Cu plating shielded alpha-particles radiated from 241Am which have almost equivalent energy to alpha-particle from lead solder.

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