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Alpha-Particle Shielding Effect of Thick Copper Plating Film on Power MOSFETs

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***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. We used americium-241 alpha-source for irradiating alpha-particles to the surface of the 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 (^{210}Pb) which become polonium-210 (^{210}Po) 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 TDDB, 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.

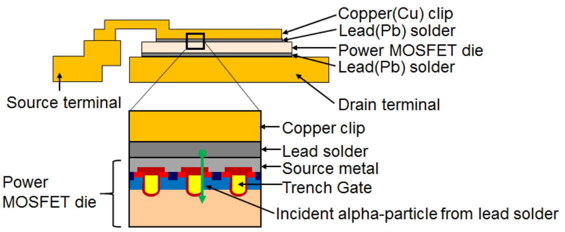

Fig. 1. A power MOSFET die mounted on copper clip package. Alpha-particles radiated from lead solder on the source metal penetrate the power MOSFET die.

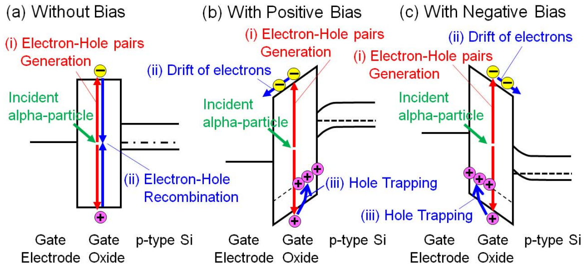

Fig. 2. Vth shift model of alpha-particle irradiation under positive or negative gate bias. Incident alpha-particles to gate oxide generates electron-hole pairs. Holes separated from electron due to gate electric field are trapped in the gate oxide.

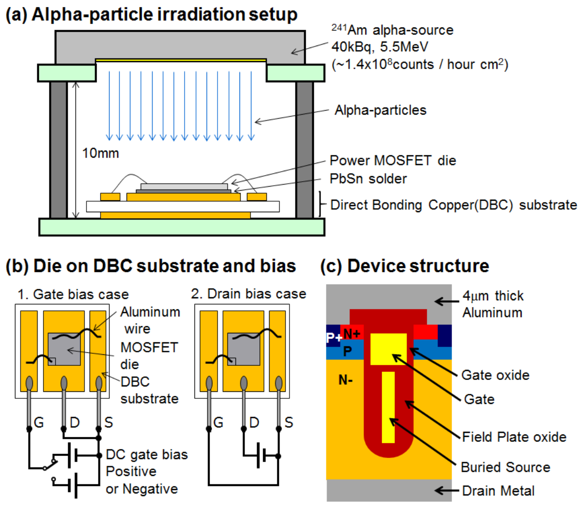

Fig. 3. (a) Alpha-particle irradiation setup, (b) Sample mounted on Direct Bonding Copper substrate and (c) Schematic device structure of the trench FP MOSFET. Alpha-particles emitted from ^{241}Am source was irradiated to the bare MOSFET chip with DC gate or drain bias.

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(^{241}Am) artificial alpha-source as shown in Fig. 3. The energy of alpha-particles emitted from ^{241}Am is about 5.5MeV. This energy is almost the same as alpha-particles energy of 5.3MeV from ^{210}Po in lead solder. The radioactivity of exploited ^{241}Am alpha-source was 40kBq, which approximately corresponded to $1.4\text{x}10^8$ counts / hour cm^2. 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 shift 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.

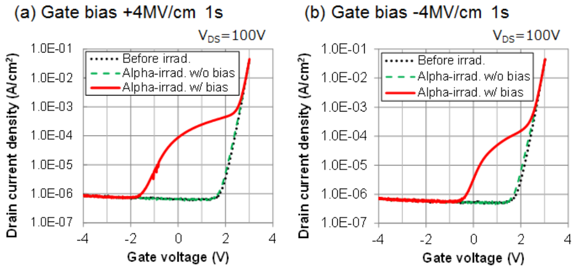

Fig. 4. Gate voltage – drain current density characteristics before and after alpha-particle irradiation without gate bias and with gate bias. The gate bias was (a) +4MV/cm 1sec. and (b) -4MV/cm 1sec. Negative Vth shift appeared both positive and negative gate bias. In contrast, no significant change was observed without gate bias.

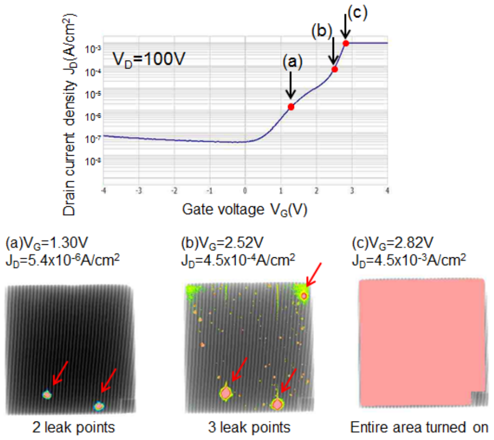

Fig. 5. Photo emission analysis of drain current leak points of after alpha-particle irradiated sample. Each spot in the active area indicated an incident point of an alpha-particle.

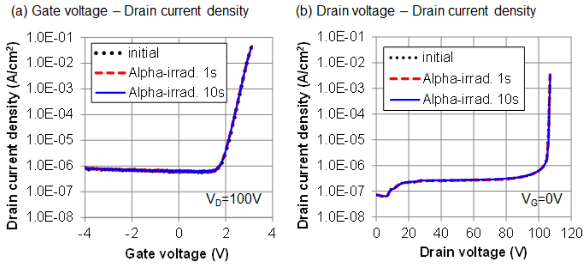

Fig. 6. Gate voltage – drain current density characteristics before and after alpha-particle irradiation under drain-source bias. Applied voltage between drain and source was 100V. No significant change was observed in alpha-particle irradiation under drain–source bias.

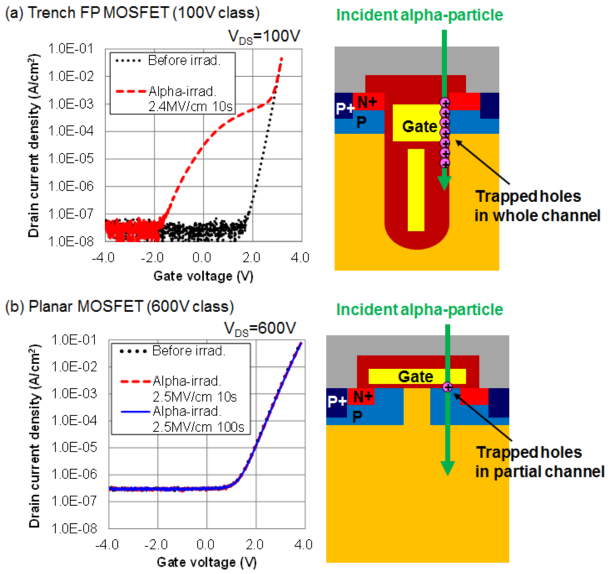

Fig. 7. Gate voltage – drain current density characteristics comparison between (a) trench and (b) planar gate structure after alpha-particle irradiation. No degradation of planar gate after 100s irradiation indicated that the trench structure is more sensitive to alpha-particle irradiation than planar structure. This difference comes from incident angle of alpha-particles to the the channel.

B. Alpha-particle sensitivety of different gate structures

Sensitivity of alpha-particle should depend on the gate structure because the Vth shift is caused by alpha-particles 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.

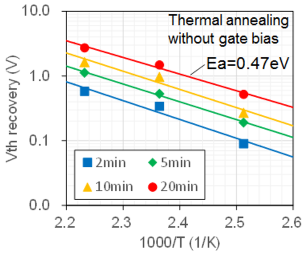

Fig. 8. Arrhenius plot of Vth shift recovery by thermal annealing. Vth was defined at drain current density 4.5×10^{-7}A/cm^2. We annealed three samples at 125, 150, 175 degrees C. Vth of each sample was measured at 2, 5, 10, 20 minutes. Activation energy of Ea=0.47eV was obtained.

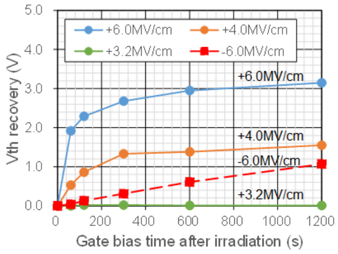

Fig. 9. Recovery of Vth shift under positive or negative gate electric field. Positive bias Vth recovery appeared over +4.0MV/cm. Vth recovery in negative gate bias is slower than that in positive gate bias.

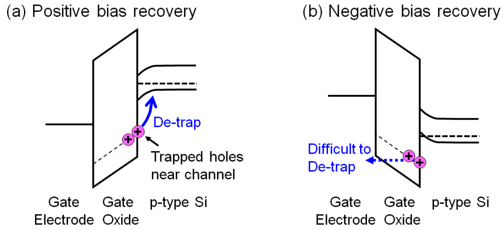

Fig. 10. Vth Recovery model under (a) positive gate bias and (b) negative bias. Trapped holes near channel are de-trapped by positive gate bias. In contrast, de-trapping is difficult under negative gate bias.

The trapped holes near the channel are significant for considering Vth influence. In the case of positive gate bias, the trapped holes near the channel de-trap to the channel side by gate electric field. In contrast, in the case of negative gate bias, these holes hardly escape to gate electrode side due to the long distance from gate electrode.

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 11.8µm 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 11.8µm 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 20µm thick Cu plated trench FP MOSFET samples. As shown in Fig. 13, 5µm thick Cu plating sample showed Vth shift as well as conventional sample in Fig. 4; and 10µm 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 ^{210}Po in lead solder. Furthermore, the possible maximum alpha-particle energy is 8.78MeV (^{212}Po) in thorium decay chain [13]; thus maximum penetration depth in Cu is estimated to 23µm. Therefore, more than 23µm thick Cu plating film must completely shield alpha-particles.

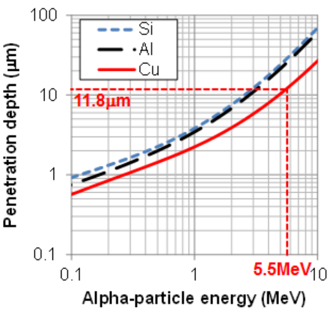

Fig. 11. Calculated penetration depth of Alpha-particle into copper (Cu), aluminum (Al) and silicon (Si). The penetration depth of 5.5MeV alpha-particles into Cu was calculated as 11.8µm.

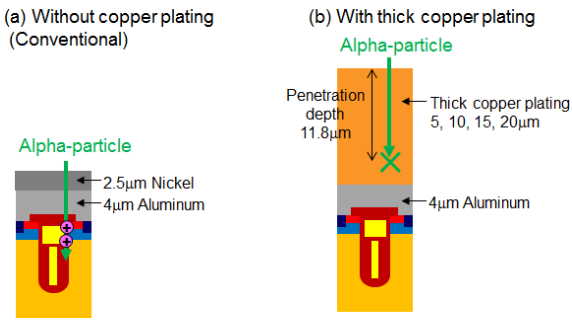

Fig. 12. The concept of alpha-particle shielding by thick copper plating film on the device. Copper plating film thicker than alpha-particle penetration depth is expected to shield alpha-particles.

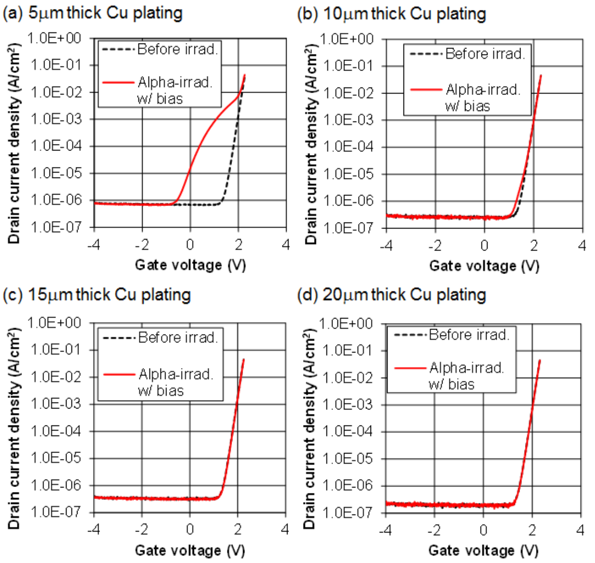

Fig. 13. Cu plating thickness dependence of alpha-particle shielding effect. These results indicated that 15 and 20µm thick copper suppressed penetration of 5.5MeV alpha-particles to the gate oxide. These are reasonable results for alpha-particles penetration depth of 11.8µm.

IV. CONCLUSIONS

We investigated Vth shift phenomena of power MOSFET by alpha-particles irradiation using ^{241}Am 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 ^{241}Am which have almost equivalent energy to alpha-particle from lead solder.

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