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Spin-Dependent Trap-Assisted Tunneling Current in Ultra-Thin Gate Dielectrics

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1. Introduction

As the gate oxide thickness of MOS structures shrinks below 2 nm, the direct tunneling current causes some critical problems for the oxide scaling. Furthermore, in such ultra-thin gate dielectrics, oxide trap levels and interface states will act as leakage sites and increase the tunneling current. The microscopic origin of the trap-assisted tunneling current is greatly desirable, especially in recently developed dielectrics, such as nitrogen-incorporated oxides and silicon nitride. To clarify the atomic structure of the leakage sites, we used an electrically sensitive magnetic resonance technique: spin-dependent tunneling (SDT) spectroscopy [1]. In this method, electron spin resonance (ESR) of the trap sites is detected by monitoring the modulated gate-current of MOS diodes in a microwave cavity in the ESR equipment.

In this study, we investigated the SDT current through a thin SiN film fabricated by low-pressure chemical vapor deposition (LPCVD). By comparing the observed signal intensity with theoretical value, we attribute the observed SDT signal to the trap-assisted tunneling current. The trap site nature will be discussed based on the g-values, their magnetic-field orientation dependence, and the bias-dependence of the signal intensity.

2. Experimental

The MOS diodes were fabricated on a p-type Si (100) substrate with 2.8-nm-thick LPCVD-SiN and with a circular aluminum gate with diameter of 500 μm. The LPCVD-SiN films showed quantitatively reproducible leakage current induced by hopping or tunneling mechanisms. The SDT measurement system is shown in Fig. 1. The diode sample was mounted in a quartz tube, and the tube was put into a cryostat that was placed in a standard TE_{102} rectangular cavity of an X-band ESR spectrometer (Bruker EMX). The resonant change of gate current at constant gate biases was detected with a two-phase lock-in amplifier using a reference signal from magnetic field modulation at the frequencies of 0.5-2 kHz. The magnetic modulation was changed in the range of 4 to 10 Gauss. To enhance the SDT signal, the sample temperature was set between 5 and 30 K. The conduction in the substrate at such low temperatures was ensured by white light irradiation on the sample surface.

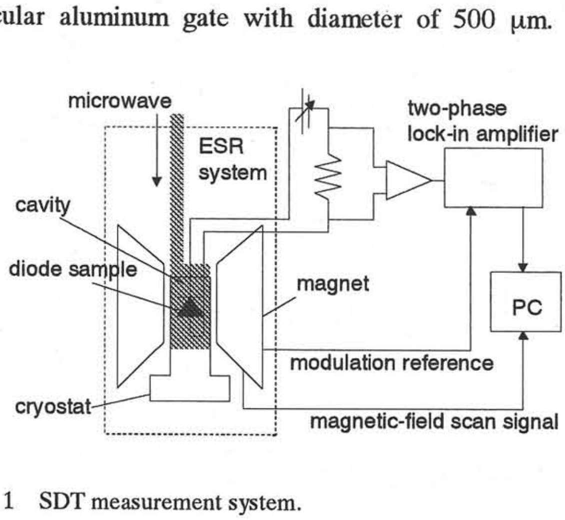

Fig. 1 SDT measurement system.

3. Model for Spin-Dependent Tunneling Current

The mechanism of SDT can be explained by the straightforward model, which was introduced to explain the spin-dependent recombination in semiconductors [2]. Figure 2 is a schematic MOS band diagram showing the conduction electron tunneling via a neutral trap level with an unpaired electron. The essence of this model is that the probability of trap-assisted tunneling depends on the relative spin orientations of the conduction electron and the trap site. The tunneling takes place only when the initial state of the system consisting of the conduction electron and trap site is singlet, because the triplet intermediate states would be forbidden at the trap site. Therefore, the relative decrease of the tunneling probability at resonance is given by the product of spin polarization of the electrons (p_e) and that of the trap sites (p_t). At sufficiently saturated condition, the maximum

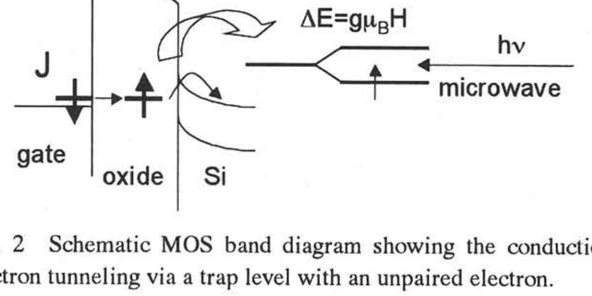

Fig. 2 Schematic MOS band diagram showing the conduction electron tunneling via a trap level with an unpaired electron.

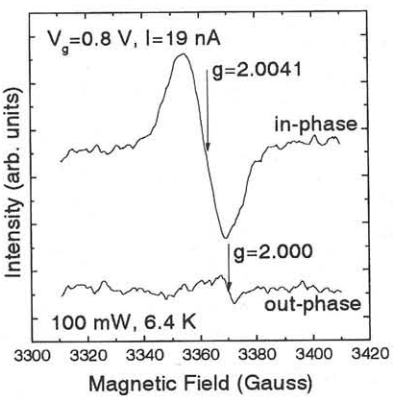

Fig. 3 Typical SDT spectrum taken at the gate bias of V_g=0.8 V.

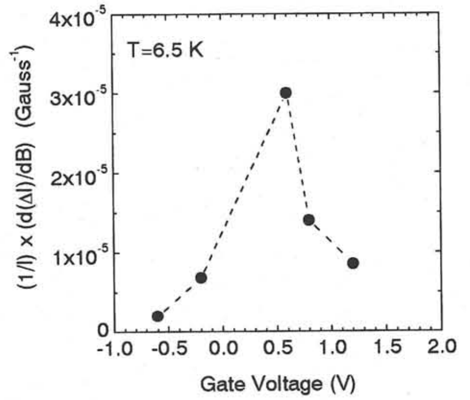

Fig. 4 Bias dependence of the normalized SDT signal.

fractional change in tunneling current at resonance is estimated to be $\Delta I/I=p_e p_t \sim (\beta H/kT)^2$, where β is Bohr magneton, H is the magnetic field, k is Boltzmann constant, and T is the temperature. Near the saturation region, the ratio $\Delta I/I$ would be expected to exhibit a microwave power (P) dependence of $\Delta I/I \propto \alpha P/(1+\alpha P)$, where α is a fitting parameter. Such dependence of $\Delta I/I$ on T and P was confirmed for our samples.

4. Results and Discussions

Figure 3 shows a typical SDT spectrum obtained at the gate bias of V_g=0.8 V. The magnetic field was set perpendicular to the sample normal (H//[011]). The phase delay respect to the modulation was tuned to maximize the SDT signal appeared in one channel (in-phase signal). We can observe a single peak at g value of 2.0041 with peak-to-peak width of 14 Gauss. In another channel spectrum, a small remaining peak is seen at around g=2.000 (out-phase). The difference in the phase delay is ascribed to the difference in the equivalent circuits for the current paths. This means that the two signals originated from different defect entities. The similar spectrum sets were observed in accumulation and depletion conditions. Under a different magnetic field orientation (H//[100]), the g value of the main signal was slightly changed (g=2.0035). Since this orientation dependence is much smaller than that of interfacial paramagnetic defects such as P_{b0} center [3], the main signal can be treated as isotropic. The orientation dependence of the out-phase signal, on the other hand, was not clear, because the signal was so small.

The bias dependence of the main signal at 6.5 K is shown in Fig. 4. The vertical axis is the current modulation normalized by the magnetic field modulation and the total leakage current. The maximum value, $3\text{x}10^{-5}$ Gauss^{-1}, was obtained at V_g=0.6 V. Near this bias, the total current decreases exponentially and changes its sign at V_g=0.4 V. This suggests that increase in the band-to-band tunneling probability would decrease the normalized SDT signal at higher biases. The current modulation of $\Delta I/I_{total}=8.2\text{x}10^{-4}$ was obtained by integrating the SDT spectrum. By comparing this with the theoretical prediction of $\Delta I/I=4.8\text{x}10^{-4}$, we estimated the trap-assisted tunneling current to be about 20% of the total current.

The isotropic nature of the main signal at g=2.004 indicates that the signal originated from the amorphous SiN film. The g value suggests that the defect responsible to the trap-assisted tunneling current might be related to the K center (g=2.003), which has been identified by ESR as a neutral paramagnetic center at a silicon atom bonded to three nitrogen atoms ($N_3\equiv Si\bullet$) [4]. The K center has been reported to be active under UV irradiation, but the SDT-active defect in our SiN films might be activated by the carrier supplied under biasing even without irradiation.

5. Summary

We have observed the spin-dependent tunneling current in MOS diodes with LPCVD SiN films. The isotropic signal at g=2.004 was attributed to the bonding defects in the amorphous SiN. The temperature dependence and power dependence of the SDT signal agreed well with those predicted by an electron polarization model, and we concluded that 20% of the leakage current flows by trap-assisted tunneling.

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