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Characterizing traps causing random telegraph noise during trap-assisted tunneling gate-induced drain leakage

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ABSTRACT

This paper presents an analysis of traps causing random telegraph noise (RTN) in trap-assisted tunneling (TAT) gate-induced drain leakage (GIDL) current. RTN was shown for the first time to occur as a result of electron trapping rather than hole trapping. In addition, the proper effective permittivity of two different materials is used to accurately determine the distance between two traps causing RTN in TAT GIDL in an oxide.

1. Introduction

Random telegraph noise (RTN) occurs when charges are randomly trapped and de-trapped from traps that have an energy level within a few kT from the Fermi level and are located in the gate oxide or at Si/SiO_2 interfaces [1–3]. Gate-induced drain leakage (GIDL) current mainly flows due to band-to-band (BTB) or trap-assisted tunneling (TAT), and it is the dominant leakage component of current in dynamic random-access memory (DRAM) cells [4,5]. RTN in the TAT GIDL current has been reported to be the primary origin of the variable retention time phenomenon that significantly affects the retention characteristics of DRAM cells [6].

Recent studies on GIDL RTN in the TAT region have been conducted, and some studies have investigated the charge trapping model that causes RTN in TAT GIDL by determining the activation energy value of the time constants [7,8], and the distance between two traps that cause RTN in TAT GIDL was determined according to the current ratio between TAT GIDL before and after electrons are captured in the capture-emission site [8–10].

However, previous studies suffered from a couple of drawbacks and limitations. First, the GIDL RTNs in the TAT region were only a result of hole trapping from the valence band, and no report so far has investigated electron trapping from the conduction band. Second, the permittivity of silicon was used to calculate the variation in the electric field instead of the effective permittivity [8,10]. These disadvantages have resulted in an inaccurate extraction of the distance between two traps.

In this study, we presented the traps that produced GIDL RTN in the TAT region. In addition, the electron trapping mechanism is reported for the first time to be based on the comparison of the activation energy value of the time constants. The proper effective permittivity for a variation in the electric field variation can be used to obtain the distance between two traps in a device in which the RTN is measured for an oxide slow trap. These analyses provide a better understanding of the physical characteristics and of the electron trapping mechanisms of traps causing RTN in a TAT GIDL current.

2. Measurement setup and background

The devices used for this experiment consisted of a planar bulk n-MOSFET with a gate length of 280 nm (sample A) and 250 nm (sample B), a gate width of 10 μm, and a gate oxide thickness of 6.9 nm. Poly-silicon is used in the devices as the gate material, and the doping concentration of the source and drain is of 9×10^{19} cm^{-3}. In contrast, the doping concentration of the substrate region is of 8.4×10^{17} cm^{-3}.

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Fig. 1(a) and (b) shows the I_D–V_{DG} curves for the devices at 323 K. Trap-assisted tunneling (TAT) can be seen to be dominant when the voltage applied between the drain and the gate V_{DG} = 4.4 V. Above that, a band-to-band tunneling current is dominant. Fig. 1(c) and (d) show time-domain two-level RTNs during TAT GIDL at a V_{DG} of 3.5–3.7 V (sample A) and 3.1–3.3 V (sample B) with 0.05 V intervals. Fig. 2 shows the cross-section of an n-MOS transistor with two traps interacting with each other. In general, only one trap is involved for RTN in drain current [3]. However, unlike this RTN, two traps are involved for RTN in TAT GIDL as shown in Fig. 2. The fast trap is just stepping-stone at the TAT GIDL current. The amplitude of electric field and capture cross section of fast trap is modulated with electron occupancy into the slow trap, which results in the fluctuation of TAT GIDL current. The RTN measurements described above indicate that the time constant ratio [$\ln(\tau_c/\tau_e)$] is a function of V_{DG}, as shown in Fig. 3 (sample A). The value of the trap depth (x_T), which is the distance between the slow trap and the interface, can be calculated by using the equation below [11].

$$x_T = \frac{T_{ox}\left[\frac{kT}{q}\frac{d\ln(\tau_c/\tau_e)}{dV_{DG}} - \frac{d\psi_s}{dV_{DG}}\right]}{1-\frac{d\psi_s}{dV_{DG}}} \tag{1}$$

With the above equation, the slope of the log of the time constant ratio can be used to obtain a trap depth (x_T) of 0.55 nm in sample A and 0.68 nm in sample B for a slow trap. In addition, the activation energy (E_a) of the TAT current was measured at 0.60 eV in sample A and 0.54 eV in sample B, respectively. It can be known that the E_a of the TAT current in each sample has relatively large value. This result can be explained as follows. The amount of energy band-bending at the drain is small in the TAT current. Thus, the fast trap should be located far above the intrinsic level (E_i) for TAT being occurred. This means that the E_a of the TAT current is large. And, this value can be used to obtain the energy level of a fast trap ($E_T - E_i$) [12]. The $E_T - E_i$ values were 0.16 eV and 0.11 eV, respectively, and Fig. 4 uses an energy band diagram to show the depths and the energy levels of the two traps in each sample.

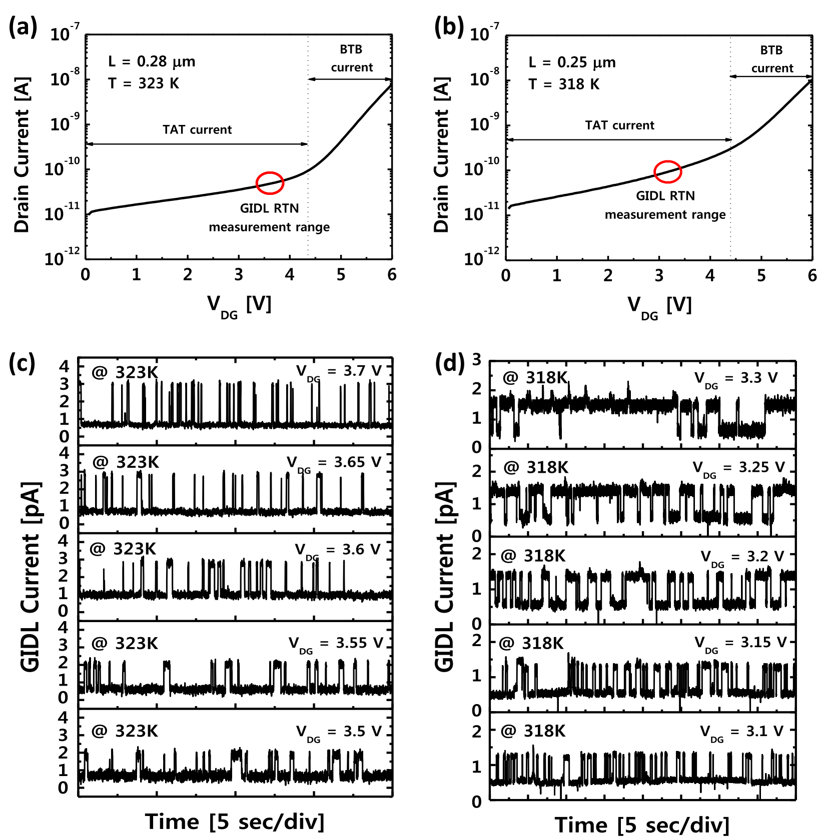

Fig. 1. I_D–V_{DG} curve for devices with RTN (a) at 323 K with W/L = 10/0.28 μm (sample A) and (b) at 318 K with W/L = 10/0.25 μm (sample B). Time-domain RTNs for a TAT GIDL current (c) at 323 K (sample A) and (d) at 318 K (sample B) with an increase in V_{DG}.

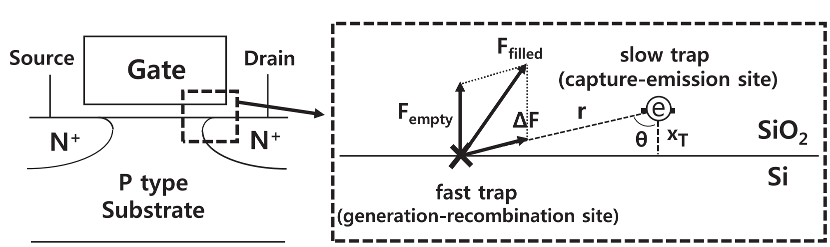

Fig. 2. Cross-section of an n-MOS transistor with two traps interacting with each other. In this figure, ΔF is equal to $q/(4\pi\varepsilon_{eff}r^2)$.