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Charge Pumping Current from Single Si/SiO_2 Interface Traps: Direct Observation of P_b Centers and Fundamental Trap-Counting by the Charge Pumping Method

Toshiaki Tsuchiya[1] and Yukinori Ono[2]

[1] Shimane Univ., 1060, Nishikawatsu, Matsue 690-8504, Japan
Phone: +81-852-32-6127 E-mail: tsuchiya@ecs.shimane-u.ac.jp
[2] Univ. of Toyama, 3190, Gofuku, Toyama 930-8555, Japan

Abstract

We made accurate measurements of the maximum charge pumping (CP) current (I_{CPMAX}) from single Si/SiO_2 interface traps, and observed for the first time that their current range is $0<I_{CPMAX}\leq 2fq$, where f is the gate pulse frequency, and q is the electron charge. This range is expected from the nature of P_{b0} centers. Based on the results and taking account of the interaction between traps in the capture/emission processes, we demonstrated fundamental trap-counting by the CP method.

1. Introduction

The charge pumping (CP) technique [1] is a highly precise method for evaluating the density of interface traps between the gate oxide and the semiconductor surface in MOSFETs. The conventional belief is that the maximum CP current (I_{CPMAX}) is given by $I_{CPMAX}=fqN$, where N is the total number of traps contributing to the current, i.e., I_{CPMAX} for a single trap is fq. We made accurate measurements of I_{CPMAX} from single traps which show that this belief is basically wrong and we demonstrate fundamental trap-counting by the CP method.

2. Maximum CP current from a single trap

CP current expected from a P_{bo} center

It is well known that P_b centers are silicon dangling-bonds at the Si/SiO_2 interface, i.e., interface traps [2]. A schematic illustration of the P_{b0} and P_{b1} densities of states for the (001) Si/ SiO_2 interface is shown in Fig. 2 [3]. When a positively charged donor-like P_{b0} center accepts an electron, it becomes neutral, and if this accepts a further electron, it becomes negatively charged, giving it a acceptor-like nature. The donor- and acceptor-like centers are distributed in the lower and upper parts of the bandgap, respectively.

The typical I_{CPMAX} from a single interface trap (a P_{b0} center) at RT is expected to be as shown in Fig. 2, depending on the pairs of discrete energy levels of the P_{b0} center involved. The energy range of the traps detected by the CP method is ±0.3 eV around midgap E_i at RT, and the boundary levels move slightly toward E_i by increasing the rise time t_r or fall time t_f of the gate pulse [1], as shown by the shaded parts in the figure. Therefore, when one of the two energy levels of a P_{b0} center is located near a boundary level (Type 1-3), then $I_{CPMAX}<fq$, and this decreases with increasing t_r or t_f,. On the other hand, Type 9 P_{b0} centers will give $I_{CPMAX}=2fq$.

Experimental results

Typical examples of CP characteristics measured from single interface traps are shown in Fig. 3, and the dependences of the characteristics on t_r or t_f in each sample are shown in Fig. 4. It has been reported that $I_{CPMAX}\leq fq$ for a single trap [4]-[7]. However, we successfully observed cases of $I_{CPMAX}=2fq$ as shown in Fig. 3, and found experimentally that the current from a single trap is indeed $0<I_{CPMAX}\leq 2fq$ as expected from the nature of P_{b0} centers.

Moreover, I_{CPMAX} for Samples A and B were independent of t_f, and that for Sample C was independent of t_r. Therefore, from these results and Fig. 4, it can be concluded that Samples A and B are Type 1, and Sample C is Type 9. Here, I_{CPMAX}, normalized by f for each sample, is constant up to at least 700 kHz as shown in Fig. 5.

3. Fundamental trap-counting by the CP method

Judging if the CP characteristics are due to a single trap

In order to count the number of multi-traps contributing to I_{CPMAX}, I_{CPMAX} has to be separated into components from each individual trap. Observing the differences in threshold ΔV_T or flatband voltage in the local area where each trap is located is effective for this purpose, as shown in Fig. 6(a). The dependences of the CP characteristics on the gate pulse width (or the on time t_{Top} and off time t_{Base}) are useful for observing the carrier capture/emission processes in individual traps [8]. These properties are quite effective in revealing the contribution from each trap, as shown in Figs. 6(b) and (c). The t_r (or t_f) dependences are also useful. From these properties, we can judge that the CP characteristics in Figs. 6(a)-(c) are due to two traps.

On the other hand, as shown in Figs. 7 and 4(c), the CP characteristics for Sample C cannot be separated by the changes in t_{Top}, t_{Base}, t_f and t_r (not shown here), which verifies that the I_{CPMAX} for Sample C is from a single trap.

We measured about 60 samples in this work, with 15 showing single trap properties; 3 with $I_{CPMAX}<fq$, 9 with $I_{CPMAX}=fq$, 1 with $fq<I_{CPMAX}<2fq$, and 3with $I_{CPMAX}=2fq$.

Interactions between interface traps

An example of the dependence of multi-trap CP characteristics on t_{Top} is shown in Fig. 8(a), where five steps are clearly seen. Each step indicates I_{CPMAX} from an individual trap, therefore, this MOSFET contains five traps. The average CP current per trap ($I_{CPMAXAV}$) and the cumulative CP current are shown in Fig. 8(b), as a function of trap number defined in Fig. 8(a). The I_{CPMAX} of trap No. 1, which appeared first, is equal to fq, and the $I_{CPMAXAV}$ monotonically decreases with the increasing number of contributing traps, which is considered to be due to interactions between traps [9]. However, since the CP current from trap No. 5 decreases with increasing t_f, as shown in Fig. 8(c), we consider the reason that $I_{CPMAX}<fq$ for trap No. 5 is because of the type of trap, i.e. Type 1-3, rather than the interaction.

4. Conclusions

We successfully observed that the range of CP current from single Si/SiO_2 interface traps is $0<I_{CPMAX}\leq 2fq$, and demonstrated fundamental trap-counting by the CP method, also considering the interaction between traps.

Acknowledgements

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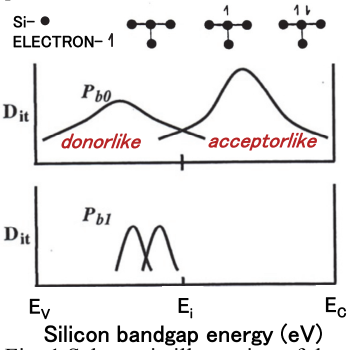


Fig. 1 Schematic illustration of the P_{b0} and P_{b1} densities of states [2][3].

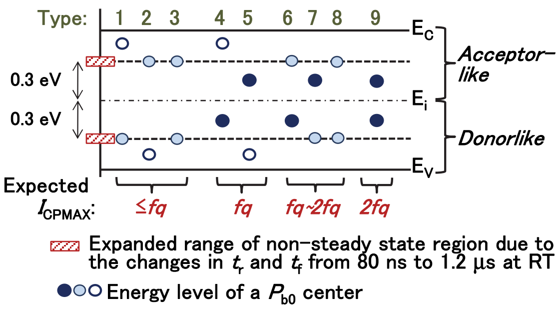


Fig. 2 Typical supposed pairs of discrete energy levels of P_{b0} centers and corresponding expected I_{CPMAX}.

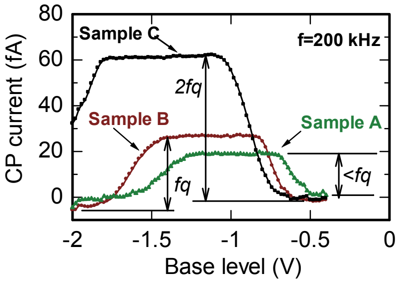


Fig. 3 Typical examples of CP characteristics of single interface traps.

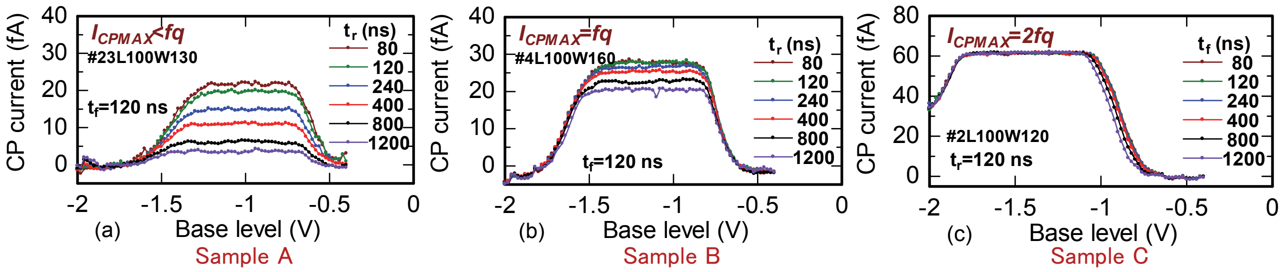


Fig. 4 CP characteristics dependences upon t_r or t_f in single traps for samples A, B, and C. t_p=5 µs, t_w=2.5 µs.

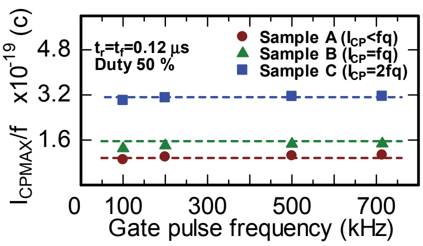
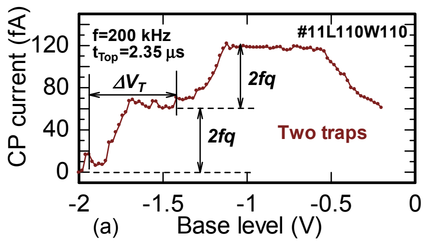
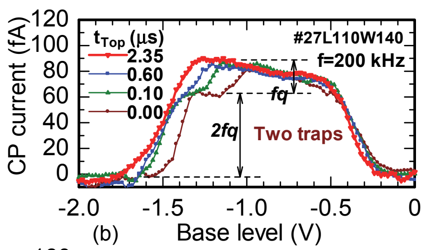


Fig. 5 I_{CPMAX} normalized by f as a function of gate pulse frequency f for samples A, B, and C.





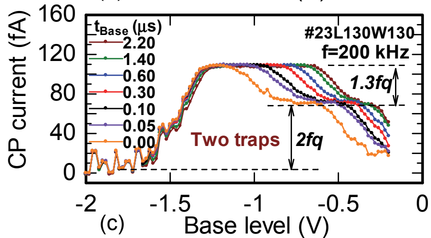
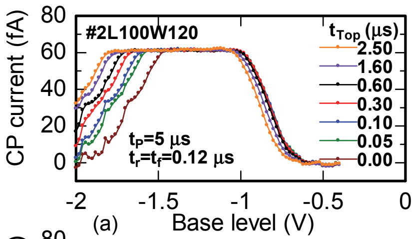


Fig. 6 I_{CPMAX} separated into components from individual traps, due to (a) the difference in local threshold voltage ΔV_T, (b) the effects of on time t_{Top}, and (c) off time t_{Base}, based on the difference in the carrier capture/emission processes in individual traps. t_r=t_f=120 ns.



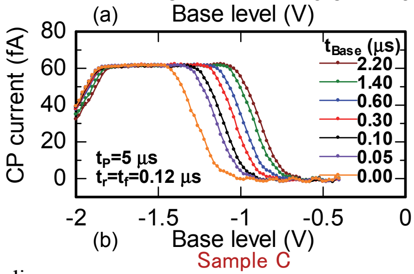
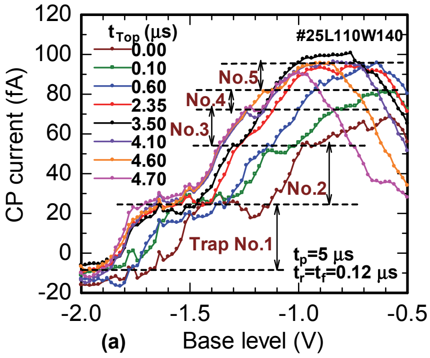
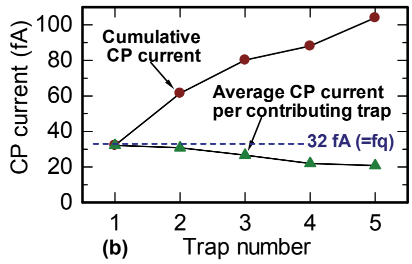


Fig. 7 Dependences of the CP characteristics on (a) t_{Top}, and (b) t_{Base} in sample C, which verify that the I_{CPMAX} is from a single trap.





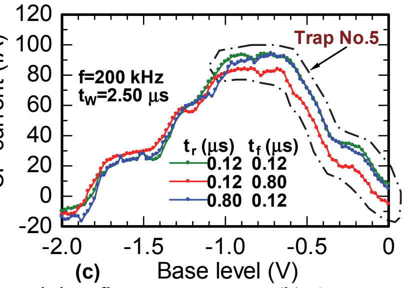


Fig. 8 (a) Dependences of CP characteristics containing five-traps on t_{Top}, (b) Average CP current per contributing trap and the cumulative CP current as a function of trap number indicated in Fig. 8(a), (c) Dependences of the CP characteristics on t_r and t_f.