Charge Pumping Current from Single Si/SiO₂ Interface Traps: Direct Observation of Pb Centers and Fundamental Trap-Counting by the Charge Pumping Method

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Abstract
We made accurate measurements of the maximum charge pumping (CP) current ($I_{CP\text{MAX}}$) from single Si/SiO₂ interface traps, and observed for the first time that their current range is $0<I_{CP\text{MAX}}<2fq$, where $f$ is the gate pulse frequency, and $q$ is the electron charge. This range is expected from the nature of Pb₀ 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 ($I_{CP\text{MAX}}$) is given by $I_{CP\text{MAX}}=fqN$, where $N$ is the total number of traps contributing to the current, i.e., $I_{CP\text{MAX}}$ for a single trap is $fq$. We made accurate measurements of $I_{CP\text{MAX}}$ 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 Pb₀ center
It is well known that Pb₀ centers are silicon dangling-bonds at the Si/SiO₂ interface, i.e., interface traps [2]. A schematic illustration of the Pb₀ and Pb₁ densities of states for the (001) Si/ SiO₂ interface is shown in Fig. 2 [3]. When a positively charged donor-like Pb₀ 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 $I_{CP\text{MAX}}$ from a single interface trap (a Pb₀ center) at RT is expected to be as shown in Fig. 2, depending on the pairs of discrete energy levels of the Pb₀ 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, one of the two energy levels of a Pb₀ center is located near a boundary level (Type 1-3), then $I_{CP\text{MAX}}=fq$, and this decreases with increasing $t_r$ or $t_f$. On the other hand, Type 9 Pb₀ centers will give $I_{CP\text{MAX}}=2fq$.

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 $I_{CP\text{MAX}}=fq$ for a single trap [4]-[7]. However, we successfully observed cases of $I_{CP\text{MAX}}=2fq$ as shown in Fig. 3, and found experimentally that the current from a single trap is indeed $0<I_{CP\text{MAX}}<2fq$ as expected from the nature of Pb₀ centers.

Moreover, $I_{CP\text{MAX}}$ for Samples A and B were independent of $t_r$ and that for Sample C was independent of $t_f$. 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, $I_{CP\text{MAX}}$, 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 $I_{CP\text{MAX}}$, $I_{CP\text{MAX}}$ has to be separated into components from each individual trap. Observing the differences in threshold $Δf_T$ 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 $t_{on}$ and off time $t_{off}$) 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 $t_{top}$, $t_{base}$, $t_r$ and $t_f$ (not shown here), which verifies that the $I_{CP\text{MAX}}$ for Sample C is from a single trap.

We measured about 60 samples in this work, with 15 showing single trap properties; 3 with $I_{CP\text{MAX}}=fq$, 9 with $I_{CP\text{MAX}}=2fq$, 1 with $fq<I_{CP\text{MAX}}<2fq$, and 33 with $I_{CP\text{MAX}}=2fq$.

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 $I_{CP\text{MAX}}$ from an individual trap, therefore, this MOSFET contains five traps. The average CP current per trap ($I_{CP\text{MAX,AV}}$) and the cumulative CP current are shown in Fig. 8(b), as a function of trap number defined in Fig. 8(a). The $I_{CP\text{MAX}}$ of trap No. 1, which appeared first, is equal to $fq$, and the $I_{CP\text{MAX,AV}}$ 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 $t_r$, as shown in Fig. 8(c), we consider the reason that $I_{CP\text{MAX}}=2fq$ 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/SiO₂ interface traps is $0<I_{CP\text{MAX}}<2fq$, and demonstrated fundamental trap-counting by the CP method, also considering the interaction between traps.

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References