Characterization and modeling of fast traps in thermal agglomerating germanium nanocrystal metal-oxide-semiconductor capacitor


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In this paper, the germanium (Ge) nanocrystals (NCs) are synthesized by using the rapid-thermal annealing and are embedded into a three-layer (SiO2/NCs–Ge/SiO2) capacitor structure. The samples with/without the postmetallization annealing (PMA) treatment are investigated to compare and study the PMA affections. The charge storage characteristics of our samples are investigated with the capacitance-voltage (C-V) hystereses. The frequency independence of hysteresis windows is found and attributed to NCs as slow traps with a large characteristic time constant. The frequency-dependent C-V and conductance-voltage (G-V) experiments are further introduced to study the interface traps and the fast traps induced by the NC formation. In order to extract the related trap characteristics from the measured C-V and G-V, we propose to utilize the equivalent circuit and single-level trap model based on Shakley-Read-Hall theory. Three associated parameters including the areal trap density, trap conductance, and semiconductor capacitances are used to confirm that the single-level trap model is truly appropriate for our samples. It is then found from the model that the areal trap density is high and approaches almost uniform distribution along the valence band and bandgap but significantly reduced and then becomes decreased from valence band to the midgap after PMA treatment. In addition, after PMA treatment, the characteristic time constant becomes smaller for one order of magnitude at the same gate bias. It is attributed to the reduction of trap density and also agrees that the interface traps are dominant and has a small characteristic time constant. © 2008 American Institute of Physics. [DOI: 10.1063/1.2953194]

I. INTRODUCTION

Many nonvolatile memory (NVM) devices, particularly floating gate devices, are approaching their fundamental limits and facing reliability issues such as tunneling-oxide scaling, charge retention, and cycling endurance. Therefore, novel devices like quantum dot or nanocrystal (NC) memories are proposed to improve their immunity against tunnel-oxide defects and reduce capacitive coupling effects.1,2 The NC NVM device, compared to the conventionally stacked-gate one, contains the charge stored in the mutually isolated crystalline NCs or dots instead of the continuous polysilicon (Si) layer to avoid the charge loss. Meanwhile, it also allows thin tunneling oxides without sacrificing nonvolatility, small operating voltages, fast write/erase speeds, and long endurance. Among those NVM devices, the metal-oxide-semiconductor (MOS) system embedded with the silicon (Si) or germanium (Ge) NCs emerges as one of the most attractive scientific research issues after the first silicon NCs memory was demonstrated in 1995.3–5 It is also reported that the system can be scaled down and still maintain good retention characteristics with the thin tunneling oxide and low voltage operation.2,3 However, the NCs have been synthesized by several methods including ion implantation,3–5 sputtering,6,7 and oxidation.8,9 It is expected that those processes easily produce defects or traps in the oxide around the NCs. They are considered as fast traps in our paper and referred as the stress effects between the NCs and oxide in the reference.10–12 The fast traps in our paper mean to have much shorter characteristic time constant \( \tau \) to exchange the carriers between themselves and the Si substrate than the NCs. Therefore, in order to optimize the device performance and stability, further clarification on the fast trap characteristics is very essential to influence the device electronic properties.

In general, the NCs may be considered as the deep or slow traps in the oxide to store the charge for a long time.13–16 The measurements such as capacitance-voltage (C-V) and capacitance versus time (C-t) are conventionally used to study the charge storage and retention effects with electrons/holes trapped in the NCs.13,15 Besides for the fast traps in the oxide around the NCs, conductance-voltage (G-V) measurement is considered to be sensitive and provides the dynamic information related to the trap density.17–19 Recently, the electron trapping, storing, and emission in SiO2/NCs–Si/SiO2 sandwich structure have been reported by using frequency-dependent C-V and G-V measurement.20 Furthermore, the NC density and great gate electric field coupling effect of NCs with high dielectric constant material...
as tunneling layer have also been estimated and studied by using the frequency-dependent $G-V$ results.\textsuperscript{21}

In our work, the Ge NCs are synthesized by using the rapid-thermal annealing (RTA) and embedded into a three-layer ($\text{SiO}_2$/NCs--Ge/$\text{SiO}_2$) structure. It is reported that the NC size and density by this method are well controlled.\textsuperscript{8} However, the process may also induce the traps or interfacial states to appear around the Ge NCs.\textsuperscript{22} Therefore, our investigation focuses on the identification and analysis of such traps which is fast in response to the applied ac signal in comparison to the NCs. The electrical performance of the slow traps, i.e., the Ge NCs, is studied with the trap characteristics from the measured $C-V$ and $G-V$ measurements. Furthermore, the postmetallization annealing (PMA) treatment is used to study the effect to reduce the defects and interfacial states. To further understand these fast traps performance, the frequency-dependent $C-V$ and $G-V$ experiments are utilized and studied on the samples with/without PMA treatment. Moreover, in order to extract the trap characteristics from the measured $C-V$ and $G-V$, we propose to utilize the equivalent circuit and single-level trap model based on Shakley-Read-Hall (SRH) theory. It is found that the PMA treatment can effectively reduce the trap density.

II. SAMPLE PREPARATION AND STRUCTURE EXPERIMENTS

A 3 nm thick $\text{SiO}_2$ layer as the tunneling oxide was first thermally grown on $p$-type (100) silicon substrate (1–10 $\Omega$ cm) in dry oxide ambient at 950 °C after the standard clean recipes. Then, a Ge layer was deposited on the $\text{SiO}_2$ layer by e-gun evaporation. A following 40 nm control oxide layer was grown by plasma-enhanced chemical vapor deposition (PECVD) system. The three-layer ($\text{SiO}_2$/Ge/$\text{SiO}_2$) structure was then heated by furnace annealing treatment in a dry $N_2$ ambient at 950 °C for 300 s. This treatment is in order to form the well-separated Ge NCs. Then 300 nm thick Al contacts were deposited on both front and back surfaces to complete the front gate and back contact of the capacitor. Finally, the gate is patterned by photolithography in the circle with $300 \mu$m of diameter. The structure characteristics of the e-gun evaporated Ge NCs embedded in $\text{SiO}_2$ matrix was measured by high-resolution transmission electron microscope (HRTEM). In addition, after Al evaporation, the sample was annealed at 400 °C in pure $N_2$ ambient as the PMA treatment to investigate the effects of interfacial traps and defects induced by the NC formation process. For comparison, the sample without PMA treatment was also fabricated from the same processes. The sample without/with the PMA treatment is defined as Sample A/B.

A cross-sectional HRTEM view of the stack with the control oxide/Ge layer/tunnel oxide structure is shown in Fig. 1(a). From lack of lattice fringes shown in the inset of Fig. 1(a), the Ge layer becomes amorphous, as expected for an electron-gun evaporated Ge film on room temperature. From the image, the thickness of Ge layer is estimated to be 4.5 nm. After the RTA treatment at 950 °C for 300 s in a dry $N_2$ ambient, the crystalline Ge NCs are formed in $\text{SiO}_2$ matrix and are shown in Fig. 1(b). The Ge NC size is about 14 nm, and the dot aerial density is estimated from image of HRTEM to be $2.4 \times 10^{11}$ cm$^{-2}$. The lattice fringes are obviously shown in the inset images and indicate the crystallization of the whole amorphous layer at 950 °C annealing treatment, which provides the enough thermal energy to agglomerate the Ge atoms due to their high diffusivity under heating.

III. MEASUREMENT RESULTS, MODELING, AND DISCUSSIONS

A. Charge storage characteristics under different frequencies

FIG. 1. Cross-sectional HRTEM images of sandwich structure with (a) evaporated Ge thin film (amorphous film is $\sim$4.5 nm) and (b) Ge NCs (the NC size is $\sim$14 nm) embedded in $\text{SiO}_2$.

The charge storage effect of our Ge NCs is investigated with the $C-V$ hysteresis. The samples in a dark box at room temperature are measured with 4284A Hewlett-Packard $LCR$ parameter analyzer controlled by a personal computer. The respective experimental results of samples A and B measured...
At two frequencies of 1000 and 100 kHz are shown in the top and bottom plots of Fig. 2. The sweeping rate (−2 V/s) of the data is fast enough to avoid the charge loss due to the thin tunneling oxide.

In Fig. 2, each hysteresis loop is composed of two different sweeps. The forward sweep is defined for the negative bias to positive bias on the metal gate, while the backward sweep is for the opposite direction. The sweeping gate voltage range is from −10 to +10 V. As a rough quantification, the hysteresis window is defined as the width between the gate voltages of the forward and backward sweeps in the hysteresis loop with the capacitance value being 0.6Cox, where Cox is the oxide capacitance and found as the maximum capacitance in strong accumulation region. The resulting windows at 1000 KHz are 8.2 and 8.9 V for samples A and B, respectively. The same results are found for the 100 kHz measurement. However, there exists a dramatically larger shift to the positive voltage for sample A than for sample B at the 100 kHz measurement. The C-V hysteresis windows measured at the various frequencies for the two samples are all shown in the inset and maintain the same value of 8.2 V (8.9 V) for our applied frequencies in sample A (B).

Especially, the little larger window for sample B than for sample A indicates that the PMA treatment has only a limited effect to avoid charge leakage in NCs; we will discuss the reason in Sec. III E.

### B. Frequency-dependent C-V and G-V measurements

Since the performance of the traps is in general frequency dependent, C-V and G-V with different applied frequencies are used to characterize them. Our measurement is between 50 and 1000 KHz with a small-amplitude (50 mV) sine-wave voltage signal. The dc bias ranged from −10 to 10 V. The measured capacitance (Cm) and conductance normalized with angular frequency (Gm/ϖ) versus the gate bias from −10 to 4 V for the forward sweep with different frequency are shown in the top and bottom plots of Figs. 3(a) and 3(b) for samples A and B, respectively. They are directly obtained by HP 4284A LCR meter. It is seen that the Cm and Gm/ϖ both shift toward more positive bias as indicated by the arrow signs for samples A than B with decreasing applied frequency. In fact, the capacitances observed in top plots of Figs. 3(a) and 3(b) are consistent with the results of Fig. 2. These shifts are defined as the variation of the gate voltage from 1000 KHz C-V curves, which are similar and close for both samples. In general, the shift toward the positive bias in the C-V curve is considered as the result of the increment of fixed negative charges or decrement of fixed positive charges. However, these predictions seem contrary to the results observed in Fig. 3(a) and 3(b).
to our previous results of the same stored charges kept in the Ge NCs. Hence, these capacitance shifts of the two samples must be considered to be a variation in their individual total capacitance, which may be caused by the charge storage of fast traps and interfacial traps. Besides, this attribution is also consistent with the shift results of the $C-V$ curves under backward sweep. In particular, the large shift is suppressed in Sample B indicates the PMA treatment could reduce the capacitance because of curing the fast traps or interfacial traps.

On the other hand, the measured conductance peak close to the capacitance transition region are also observed in the $G_m/\omega$-$V$ measurement in bottom plots of Figs. 3(a) and 3(b). The peaks of $G_m/\omega$-$V$ curves are shifted in accord with that of $C_m$-$V$ curves. The $G_m/\omega$-$V$ curves of Sample B have comparatively sharper and smaller peaks than those of Sample A, which is attributed to having higher energy loss during charge exchange. The inset of Fig. 3(b) shows the $G_m/\omega$-$V$ and $C_m$-$V$ curves at 1000 KHz for Sample A and Sample B respectively. The breadth of the $G_m/\omega$-$V$ curves is related with the stretch-out of $C_m$-$V$ curves along the bias axis. This result strongly indicates that the $G_m/\omega$-$V$ curves are sensitive to the transition of the substrate capacitance. Moreover, compared to $G_m/\omega$-$V$ characteristics of the samples, the greater and broader peaks are found in sample A than in sample B; these phenomena may be rendered by a lot of fast traps in the defective oxide between the Ge NCs, and the substrate causes more energy loss and contributes to the conductance characteristics. On the other hand, the PMA treatment may suppress the capacitance shifts and conductance peaks dramatically in sample B. It is suggested that PMA treatment can cure the fast traps.

However, it is still complicated to clarify the trap characteristics from variation of the measured capacitance shifts and conductance peaks. The associated capacitance and conductance of trap are necessary to be found for further deliberating upon the related mechanisms. It is hence worthwhile to mention the equivalent circuit model suggested by Nicollian and Brews to find the associated trap conductance ($G_T$) and capacitance ($C_T$) with the $C_m$ and $G_m$.\textsuperscript{17}

C. Utilizing equivalent circuit to extract the trap conductance

In our samples, it is found that the position of traps is close enough to the Si/SiO\textsubscript{2} interface, and then the equivalent circuit of our devices can be approximated as the one shown in Fig. 4. Among them, $C_{ox}$ is the oxide capacitance, $C_r$ represents the semiconductor capacitance close to the oxide interface, and $C_T$ is the trap capacitance. The sum of previous latter two capacitances is denoted by the parallel capacitance $C_p$. In addition, $G_T$ is the trap conductance and also named as $G_p$, i.e., the parallel conductance which is parallel with $C_p$. The series resistance $R_s$ is used to represent the bulk and back contact resistances. According to Ref. 17, $R_s$ is determined by biasing the device into the accumulation with $R_s = G_{ma}/(G_{ma}^2 + \omega^2 C_{ma}^2)$, where $G_{ma}$ and $C_{ma}$ are the measured conductance and capacitance, respectively, in the strong accumulation. With the known $C_{ox}$ and $R_s$, the $G_p$ and $C_p$ can be calculated from $G_m$ and $C_m$.

The resulted experimental values of the $G_p/\omega = G_T/\omega$ versus the gate voltage are illustrated first in Fig. 5 and have been approximated to be two orders larger in the peak magnitudes than those of $G_m/\omega$ for both samples. In addition, sample A has wide conductance peaks while sample B shows narrow peaks but small magnitude for the same applied frequency. It indicates that PMA treatment is effective to reduce the energy loss from the charge exchange. It is also seen that the conductance peak of sample B is decreasing with lowering the applied frequency. This phenomenon is referred as a typical response from interface traps\textsuperscript{17,21} and also indicates that the traps around the NCs are almost cured by the PMA treatment in sample B. On the other hand, the peak magnitudes of sample A do not show this trend with the applied frequency.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{Fig4.png}
\caption{(Color online) Schematic diagram of equivalent circuit model for a NC MOS structure, where $C_{ox}$=oxide capacitance, $C_r$=semiconductor capacitance, $C_T$=trap capacitance, $C_p$=parallel capacitance, $G_p$=$G_T$=trap conductance, and $R_s$=series resistance.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{Fig5.png}
\caption{(Color online) The trap conductance ($G_T/\omega$) vs gate voltage for samples A and B. It shows the narrower distributed peak and reduction of magnitude after PMA treatment.}
\end{figure}
frequency. It may be attributed to the traps around the NCs caused by the NC formation. Moreover, compared with the $G_m/\omega-V$ curves, the peak positions in both samples are shifted toward the left along the gate voltage axis. It is also an interesting observation that through PMA treatment, the conductance peak magnitudes at the low applied frequency are reduced more drastically than the high ones. Thus, comparing the associated peak positions for the same applied frequency, we find that the peak position of sample A is on the right side of that in sample B in the $G_m/\omega-V$ figure but becomes on the left side in the $G_T/\omega-V$ figure.

Hence, in order to further understand those phenomena, the $C_T$ values must be found. In the next two sections, we will use a trap model and the related parameters to derive the trap characteristics which can explain our experimental and analyzed results.

D. Utilizing trap model to extract the trap characteristics

In fact, it is noted that obtaining $C_T$ directly from $C_p$ = $C_s$ + $C_T$ is still impossible since $C_s$ is also unknown. In order to find the $C_s$ and $C_p$, the single-level trap model is proposed for simplicity and we tried to obtain $C_T$ from $G_T$ because the theoretical formulas for $G_T$ (= $G_p$) and $C_T$ are correlated. In particular, the substrate of our device is doped with $p$-type impurity of about $10^{15}$ cm$^{-3}$. The related energy band diagram is shown in Fig. 6. Even in some weak accumulation regime, the Fermi level does not enter into the valence band. Therefore, the density of states for holes increases with the hole energy increment in the valence band, but the occupation probability of the hole states decreases. On the other hand, in the depletion regime, due to the Fermi level away from the valence band, the occupation probability of the hole states decreases exponentially with the hole energy increment, but the tunneling probability for the holes through the depletion barrier increases exponentially. In both situations, it is always expected that the distribution for the injected holes to the oxide should have a peak along the energy axis and peak energy can move with the applied bias. Hence, the single-level trap model with the same energy as the peak energy is expected to exchange the holes with the substrate. Such traps may exist in the interface between the oxide and substrate or NCs. Based on this model and SRH recombination theory with the small signal approximation for the hole as the majority carrier, the admittance $Y_T$ of the single-level traps is given by the following expression:

$$Y_T = \frac{\omega^2 \tau A + j \omega A}{1 + (\omega \tau)^2} = G_T + j \omega C_T,$$

where $\omega$ is the angular frequency, $\tau$ is the characteristic time constant for the hole exchange between the trap and substrate, $G_T$ is the trap conductance to represent the energy loss from carrier exchange, $C_T$ is the trap capacitance to store the charge, and $A$ is a positive constant which is proportional to the trap areal density. Among them, the $\tau$ and $A$ are related to the energy level of the trap and hence are voltage dependent as shown in Fig. 6. Furthermore, we can obtain $C_T$ from $G_T$ as follows:

$$C_T = \frac{G_T}{\omega^2 \tau},$$

Combining Eq. (2) with $C_p = C_s + C_T$ gives the following formula:

$$\frac{G_T}{\omega^2} = \tau (C_p - C_s).$$

Since $C_s$ is determined primarily with depletion thickness of the substrate, it is independent of $\omega$ and related to the bias voltage only. The experimental values of $G_T/\omega^2$ vs $C_p$ at five different frequencies ($50$–$1000$ KHz) from $V_g = 9$ to $-6$ V by steps of $0.5$ V for sample A are shown with five respective solid symbols in Fig. 7. The solid lines which connect the solid symbols under the same respective gate voltage demonstrate a linear relationship. The similar results also occur in sample B, and it confirms that Eq. (2) is true for both samples. According to Eq. (3), the slope of the line is $\tau$.
and the intercept of the $C_p$ axis is $C_s$. Consequently, we can use the resulting $\tau$ and $G_T$ formula in Eq. (1) to derive the values of $A$ in both samples as follows:

$$A = G_T \left[ \frac{1 + (\omega \tau)^2}{\omega^2 \tau} \right].$$

Finally, the $C_T$ is able to be evaluated with $C_T = C_p C_s$. The experimental results of above parameters will be discussed in the following section.

E. Modeling results and discussion

In this section, among the first three sections, we are going to present and discuss the modeling results in the sequence of the trap characteristic $A$ and substrate characteristic $C_s$, characteristic time constant $\tau$, and trap characteristics $C_T$ and $G_T$. The arrangement of the following sections is first to confirm the model and then to discuss the physical mechanism. Extra more discussions are involved in Sec. III E 4.

1. Trap characteristic $A$ and substrate characteristic $C_s$

The values of $A$ calculated with Eq. (2) are shown in Fig. 8. The bias range is limited from the weak accumulation to depletion regimes. It is found that the variations of resulting $A$ versus gate bias almost have the same trend and almost indicates independence from frequency in both samples. The inset shows averaged values of $A$ for the five different frequencies and corresponding stand and deviations in both samples.

FIG. 8. (Color online) The resulted values of $A$ are calculated with Eq. (2) for both samples. The bias range is limited from the weak accumulation to depletion regimes. It is found that the variation of resulting $A$ vs gate bias almost has the same trend and almost indicates independence from frequency in both samples. The inset shows averaged values of $A$ for the five different frequencies and corresponding stand and deviations in both samples.

In addition, the values of $G_T/\omega$ are able to be calculated with the $G_T$ formula in Eq. (1) and the evaluated $\tau$ and averaged $A$ for five different frequencies. The comparisons of the calculated $G_T/\omega$ and experimental $G_T/\omega$ are shown in top and bottom plots of Fig. 9 for samples A and B, respectively. In the two samples, the calculated results are much more consistent with experimental ones for sample A than for sample B. The origin of larger error for sample B than for sample A actually comes from the comparative signal reduction after the PMA treatment. Furthermore, the inset of Fig. 9 shows the extracted $C_s$ from Eq. (3) of samples A and B. It demonstrates the similar variations and magnitudes of $C_s$ for both samples.

FIG. 9. (Color online) The $G_T/\omega$ are obtained experimentally and calculated theoretically for samples A and B with individual applied frequency from $G_T$ formula in Eq. (1). The inset shows the extracted $C_s$ from Eq. (3) of samples A and B. It demonstrates the similar variations and magnitudes of $C_s$ for both samples.

In the trap model, $A$ is proportional to the areal density states of fast trap ($A \approx D_f$). Obviously, the larger $A$ which is evaluated in samples A than B indicates that the less fast traps exist in sample B. This reduction of trap density strongly agrees with PMA treatment. Besides, the calculated averaged $A$ also shows the little increment and then flat bias dependence in sample A but a slight decrement in sample B along the forward sweep bias. The bias dependence of sample A implies that the fast trap density versus energy level approaches almost uniform distribution, which may also be the cause of the broad distribution of $G_T$ along this...
bias range in sample A. On the other hand, the A decrement along the forward sweep bias in sample B is attributed to the reduction of the fast traps. In particular, the forward sweep bias moves the Fermi level from the valence band into the bandgap. Therefore, the decrement of A in sample B indicates that the fast trap density is decreased from valence band to the midgap. The result is consistent with the phenomenon of the interface trap between oxide and substrate.

The PMA treatment hence almost cures the fast traps induced by the NC formation. The corresponding $G_T$ in sample B hence become smaller and narrower than that in sample A.

2. Trap characteristics $\tau$

The extracted values of $\tau$ are presented in Fig. 10 by the curves with solid squares and circles for samples A and B, respectively. The $\tau$ stands for the dynamic property between traps and substrate. It ranged from submicroseconds to microseconds, and it gets larger exponentially along the forward sweep bias in both samples. Actually, $\tau^{-1}$ is the exchange rate of the holes between the traps and substrate and should be proportional to the injection hole density. As shown in Fig. 6, the injection hole density is expected to become decreased exponentially along the forward sweep bias, i.e., from the weak accumulation into the depletion regimes. It hence agrees well with the $\tau$ increasing exponentially. In addition, after PMA treatment, the $\tau$ becomes smaller by one order of magnitude at the same gate bias. As shown in Fig. 6, it is expected that the $\tau$ of fast traps induced by the NCs formation and near the interface is larger than that of the interface traps because the additional tunneling path through the oxide for the holes is needed to reach the fast traps. Therefore, after the PMA treatment, sample B has the dominant interface traps, which are demonstrated in Fig. 8, and indeed shows a smaller $\tau$ than sample A.

3. Trap characteristics $C_T$ and $G_T$

The top and bottom plots of Fig. 11 show the $C_T$ variations versus gate bias under the five different frequencies in samples A and B. They are calculated with $C_T=C_p-C_s$ as described in Sec. III D. It is obvious that the $C_T$ variations have the similar bias dependence, and its magnitudes increase with the frequency decreasing. Especially in the depletion regime ($V_G=-8$ to $-6$ V), the $C_T$ variations are similar with that of $C_s$ as shown in Fig. 11. It is also implied in the simplified equivalent circuit of Fig. 4 that $C_T$ is shunted with $C_s$ and may hence be regarded as an additional $C_s$ especially in the depletion bias regime. Therefore, the shifts of $C_m$-$V$ curves can be explained with the additional contribution to the $C_s$ from the $C_T$ under the different frequencies. On another hand, the $C_T$ shows more dramatic increment with decreasing applied frequency in sample A than in sample B. According to the $C_T$ formula in Eq. (1), the $C_T$ results are significantly associated with the values of $A$ and $\omega \tau$ which are the important terms to contribute to the value of $C_T$. As shown in Figs. 8 and 10, the $A$ and $\tau$ of sample A are much larger than those of sample B. According to the formula in Eq. (1), the large $A$ and $\tau$ will do larger contribution to the value of $C_T$ especially at low applied frequency. This can explain the $C_T$ behavior found in Fig. 11.

Moreover, it is also observed that the $G_T/\omega$ peak is a little larger in sample A than in sample B under high applied frequencies but becomes much larger under low applied frequencies. Theoretically, it is expected that $G_T/\omega$ peak occurs at $\omega \tau=1$ as shown in $G_T$ formula in Eq. (1). The trend of peak distribution is consistent with that of $A$ in Fig. 8. In addition, as shown in Fig. 4, about the $G_m/\omega$-$V$, it is found that the $G_m/\omega$ peak position for sample A is always on the right side of that for sample B under the same applied frequency. However, in Fig. 5, about the $G_T/\omega$-$V$ curves, it always appears on the left side. This phenomenon can be explained with the $\tau$ reduction after PMA treatment. Since the $G_T/\omega$ peak position occurs at $\omega \tau=1$, the associated gate
bias $V_G$ with $G_T$ peak is determined with $\tau(V_G)=1/\omega$. For the same applied frequency on samples A and B, their $G_T/\omega$ peak positions should occur at the same $\tau$ value. As shown in Fig. 10, for the same $\tau$ value, the corresponding bias for sample A is always on the left side of that for sample B. This agrees with the results shown in Fig. 5 about the $G_T/\omega-V$ curves. On the other hand, the peak position of the $G_m/\omega-V$ curve is not the real peak position of $G_T/\omega-V$ due to the distortion of the $C_{ox}$ on the measured $C_m$.

4. Additional discussions

As mentioned earlier, the charges kept in the NCs are almost the same in samples A and B and are not affected by the applied frequency. Even for sample A with many fast traps near the Si/SiO$_2$ interface, the charges do not leak out with the assistance of the fast traps. In fact, as shown in Fig. 6, the stored charges are attracted and pulled by the negative gate bias from the weak accumulation to depletion regimes. The related energy band diagrams are clearly shown in Fig. 6 for the weak accumulation regime and its inset for the depletion regime. This is consistent with the little larger $C_V$ hysteresis window for sample B than for sample A found in Fig. 2. The PMA treatment has only a limited effect to avoid charge leakage in NCs in our device.

As noted in Refs. 17 and 22, the PMA treatment with RTA is considered as a kind of release of hydrogen, which is well known to efficiently neutralize dangling bonds and interface traps. This neutralization is also called passivation and involves the removal of the energy levels in energy band or bandgap. Therefore, the neutralization may be attributed to the cause of the PMA treatment to cure the fast traps in sample B.

IV. CONCLUSION

Thermal agglomerating Ge NCs synthesized with RTA are embedded into SiO$_2$ to form MOS capacitor. The samples with/without the PMA treatment are used to compare and study the PMA affection. The charge storage characteristics of our samples are investigated with the $C-V$ hystereses. The frequency independence of hysteresis windows is found and attributed to NCs as slow traps with the $\tau$ being too large to respond to the applied frequencies. In addition, the significant shifts toward the positive bias with decreasing applied frequency in the $C-V$ curve are observed and assumed to originate from the fast traps induced by the NCs formation.

To further understand this fast trap performance, the frequency-dependent $C-V$ and $G-V$ experiments are utilized and studied on the samples. Moreover, in order to extract the related $G_T$ and $C_T$ of the trap from the measured $C-V$ and $G-V$, we propose to utilize the equivalent circuit and single-level trap model based on SRH theory. By comparing the evaluated $A$ and $\tau$ of samples from the trap model, it is demonstrated that the trap density is significantly reduced by the PMA treatment and the interface traps are finally dominant after PMA treatment. Besides, the frequency independence of $A$, the results of calculated $G_T/\omega$, and the extracted $C_T$ all confirm that the single-level trap model is truly appropriate for our samples. Lastly, the result of the trap reduction supports that the PMA treatment is efficient to cure the fast traps.

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