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Influence of High Electric Field Capture and Emission of a Deep-Level Center in VLSI Device Structures

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Two new techniques, reverse-bias pulsed deep-level transient spectroscopy (RDLTS) and injection deep-level transient spectroscopy (IDLTS), for use in measuring electric field dependent carrier emission and capture rates, respectively, are described in detail. The Au donor center at E_V + 0.35 eV was studied by these two methods as an example. The results indicate that the carrier emission rate increases and that the carrier capture rate decreases in the presence of high electric field. The implication of the enhanced emission and retarded capture is discussed in terms of leakage current and premature breakdown in VLSI device application.

I. INTRODUCTION

The study of deep-level defects in semiconductors is extremely important since the presence of deep-level defects causes the leakage current to increase and the current gain of bipolar transistors to decrease. In the case of CMOS DRAM cell, the signal storage capacitor has to have a long carrier lifetime in order to preserve the signal between refreshs. In VLSI, the electric field strength in the devices continues to increase as device geometry is continuously scaled down according to scaling rules. The presence of this high electric field can influence the properties of the deep-level defects and thus the performance of these devices. It is extremely important to characterize the carrier emission and capture kinetics of the deep-level defects at high electric field. Previously, several methods were attempted to measure the high field carrier emission rate but none was found convenient to use or accurate in giving data.[1,2] A new technique, reverse-bias pulsed deep-level transient spectroscopy (RDLTS), has been recently proposed to determine the electric field dependence of carrier emission rate accurately and conveniently.[3] In this paper, the theory of RDLTS will be described in detail. Moreover, a dual technique, designated as injection deep-level transient spectroscopy (IDLTS), is used to measure the electric field dependence of capture rates. The IDLTS is a simple and accurate method to resolve the previous difficulties in accurately determining the carrier capture rates.[4] In experiments, the Au-center in Si was studied using both methods to illustrate the validity of these two techniques.

II. THEORY

The basic concept of RDLTS is to use an emission pulse, rather than a capture pulse as in the case of conventional DLTS, to superimpose on a reverse D.C. bias. The empty state concentration in a narrow region is controlled by either varying the emission pulse height or changing the pulse duration. Thus, the transient capacitance signal amplitude is directly related to the emission pulse waveform. It has been shown previously that the true transient signal actually comes from the capture of electrons by defect states in the narrow region near the intersection point of the Fermi level and the defect level.[3] By considering the emission mechanism during the application of the emission pulse as well as the capture dynamics during the capacitance transient observation, the capacitance transient for a one-sided abrupt junction can be expressed as

$$\frac{\Delta C(t)}{C} = \int_0^1 dz \, \frac{N_t(z)}{N_D(z)} \left[1 - \exp\left(-t_p/\tau_e(\varepsilon)\right)\right] \cdot \exp\left(-t/\tau_c(z)\right)\left(1 - z\right) \quad \text{and } z = 1 - \frac{x}{w} \qquad \text{Eq. 1}$$

where both the defect and shallow dopant concentrations N_t and N_D, respectively, are functions of distance; x is the position of defects inside the depletion region; w is the depletion width and can be calculated from the depletion approximation with a given reverse D.C. bias V_b. It is noted that z is a dimensionless coordinate running from 0 to 1, or correspondingly from the n-side depletion edge to the p^+ side. The two factors, $\tau_e(\varepsilon)$ and t_p inside the integral, are the emission time constant and the emission pulse width, respectively, and these two factors control the transient signal amplitude. The transient observation time t, set by a boxcar averager, and spatial dependent capture rate $\tau_c(z)$ also control the measured transient signal amplitude. However, since the emission and capture processes are two oppositely directed functions of temperature,[3] there is a maximum ΔC in the temperature scan for a given emission pulse width t_p when measured using a two-channel boxcar averager. In such a measurement, the capture of electrons within the depletion region in a narrow region near x_o, the point of intersection of the Fermi level and the defect level, is detected. A detailed description of these two mechanisms of emission and capture can be found in Ref. 3. It is noted that Eq. 1 is valid only when $\Delta C \ll C$, the condition that is usually met for transient capacitance measurements in the case $N_t \ll N_D$.

In applying RDLTS to determine the field enhanced carrier emission rate, it is worth noting again that the transient signal observed comes from capturing of carriers by the empty deep-level states located in an extremely narrow region. The understanding of this high spatial resolution is essential in giving highly accurate results without the knowledge of spatial distributions, as well as in determining precisely the electric field strength at which the carriers emit. During the application of the reverse-bias emission pulse in the experiment, the carrier emission occurs in the depletion region prior to capturing. The empty state concentration after the application of the emission pulse is determined by the pulse width and height, and the latter determines the applied electric field strength. From the change of the subsequent transient capacitance, the emission rate as a function of the pulse height (and the electric field strength) can be obtained as described implicitly in Eq. 1. The spectrum obtained with this RDLTS along with the conventional DLTS spectrum is shown in Fig. 1. The up-going spectrum is indicative of carrier capture in contrast with the down-going conventional emission DLTS spectrum. With this technique, the nonuniformities of the deep-level defect and the dopant concentration distributions do not affect the accuracy of the measurement.

A duality to the RDLTS technique is the injection DLTS (or IDLTS), which is based on a similar principle of RDLTS with an additional injection means to supply majority carriers for capturing when the reverse-bias pulse is still applied. This is accomplished by the use of a bipolar transistor structure. As indicated in Fig. 2, an injection pulse V_I is applied to the emitter-base junction at the same time when the reverse-bias pulse V_p is applied to the base-collector junction. During the injection pulse period, carriers are injected from the emitter through the base and into the collector region, and are subsequently swept out by the electric field in the depletion region created by the reverse-bias pulse applied at the base-collector junction. During the application of reverse-bias pulses in the collector, not only the injected carriers are captured inside the depletion region (collector side), but also the captured carriers can emit from the defects in the depletion region. As a result, the nature of the subsequent transient capacitance signal, observed in the collector as indicated in time t_1 and t_2 after the injection pulse is removed, depends on whether the carrier capture or the carrier emission is dominant. If the carrier capture rate is higher than the carrier emission rate, the transient capacitance signal due to carrier emission similar to the conventional DLTS is observed, i.e. a down-going spectrum. If, on the other hand, the carrier capture rate is lower than the carrier emission rate, the observed transient capacitance signal will be dominantly due to carrier capture similar to RDLTS. In the former case, the difference between IDLTS and DLTS lies in the source of the majority carrier supply, i.e. from the emitter in IDLTS and from the quasi-neutral bulk region for DLTS. These two competitive capture and emission processes can be described by the following equation, which can be derived similarly to Eq. 1:

$$\frac{\Delta C}{C} = \int_{o}^{1-\frac{x_o}{w}} dz \left(\frac{e_p(\varepsilon)}{c_p(\varepsilon) + e_p(\varepsilon)} \right) \cdot \frac{N_t(z)}{N_A(z)} \quad .$$

$$\left[1 - \exp\left(-t_p/\tau_p(\varepsilon)\right)\right] \cdot \exp\left(-t/\tau_c(z)\right) \cdot (1 - z)$$

$$- \int_{1-\frac{x_o}{w}}^{1} dz \left(\frac{c_p(\varepsilon)}{c_p(\varepsilon) + e_p(\varepsilon)} \right) \cdot \frac{N_t(z)}{N_A(z)}$$

$$\left[1 - \exp\left(-t_p/\tau_p(\varepsilon)\right)\right] \cdot \exp\left(-t/\tau_{po}\right) \cdot (1 - z)$$

$$\text{and} \quad \frac{1}{\tau_p(\varepsilon)} = e_p(\varepsilon) + c_p(\varepsilon) \qquad \text{Eq. 2}$$

For a pnp transistor, the junction capacitance given in Eq. 2 is for the n^+-p collector junction, x_o is the intersection point of the Fermi level and the defect level, τ_{po} is the hole emission time constant in low electric field during transient observation, $\tau_c(z)$ is the spatial dependent capture time constant for holes similar to those in Eq. 1, t_p is the emission pulse width, and $e_p(\varepsilon)$ and $c_p(\varepsilon)$ are the emission and capture rates for holes, respectively. The latter two parameters are both strong functions of electric field. However, $e_p(\varepsilon)$ is also a strong function of temperature while $c_p(\varepsilon)$ depends on the injected carrier concentration or the injection current. In Eq. 2, the first part describes the emission-dominated RDLTS effect during t_p and the transient capacitance signal becomes positive if this part predominates. The second part of Eq. 2 expresses the capture-controlled DLTS effect during t_p and if this part becomes more significant the resulting transient capacitance signal is negative. By applying a constant-current pulse while varying the reverse pulse width and height, the change of the transient capacitance signal can be used to calculate the electric field dependent carrier capture rates. The IDLTS spectrum obtained is shown in Fig. 3 for different pulse heights with a given pulse width. As seen in Fig. 3, the transient capacitance signal decreases as the pulse height (or electric field) increases. This indicates that the effect of carrier capture retardation is the presence of high field. Detailed derivation of these equations along with the physical origin of the retardation effect will be published elsewhere.[5]

III. EXPERIMENTAL RESULTS

In experiments, Au-doped silicon pnp transistors were studied using the RDLTS and IDLTS methods. The energy levels at lower field were determined to be $E_V + 0.35$ eV and $E_c - 0.56$ eV, for donor and acceptor levels respectively, using the conventional DLTS method. The capture cross section for the $E_V + 0.35$ eV center was obtained to be about 5E-16 cm^2. In order to obtain accurately the enhancement factor, the emission pulse width and height were adjusted at the same time to keep the transient capacitance signal constant. The ratio of the pulse widths used in the high and low fields can directly be used to calculate the enhancement factor given in Table 1. The enhanced carrier emission rates at different temperatures are also shown explicitly. The results indicate that the lower the temperature is, the higher the enhanced emission factor is. The retarded carrier capture rates at different temperatures were measured using IDLTS. The retardation of the carrier capture along with the enhancement carrier emission are illustrated in Fig. 4. The measured data of the enhanced emission rate indicates that the Au donor level at $E_V + 0.35$ eV has a polarization potential well, and the retarded capture rates show that the decrease of capture cross section correlates with the increase of the phonon emission rate when hot carriers are captured. The detailed discussion on emission and capture of mechanisms will appear elsewhere.

IV. CONCLUSION

Two techniques have been used to measure electric field dependent carrier emission and capture rates accurately and conveniently. The RDLTS results indicate that the emission rate is increased in high field, which in turn implies a shorter effective carrier generation lifetime. However, a reduced carrier capture rate in high field suggests a longer minority carrier recombination lifetime. In VLSI, devices are scaled down and present becomes higher, and the enhancement in carrier emission from the defects can cause an immature breakdown and an increase in leakage current under a reverse bias condition.

References

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TABLE 1

pulse width (μs)	pulse height (v)
390	0.5
390	1.0
390	2.0
340	4.0
310	6.0
250	10.0
180	15.0
90	20.0
65	25.0
50	30.0
40	35.0

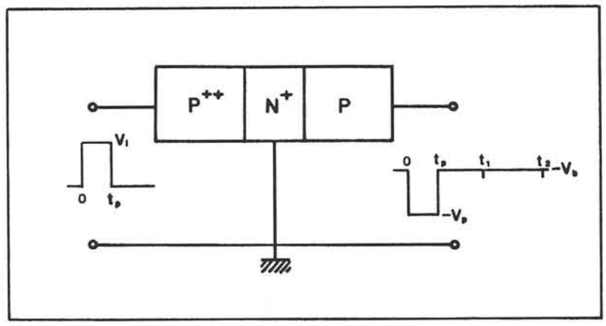

FIGURE 2. A pnp transistor structure used for IDLTS study. The emitter-base junction is forward-biased by an injection pulse V_I. The electric field in the base-collector junction varies by the reverse-bias pulse V_p. Both V_p and V_I are applied simultaneously.

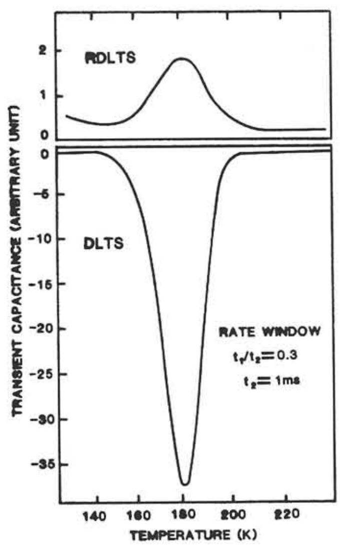

FIGURE 1. Typical DLTS and RDLTS spectrum for the E_V + 0.35 eV Au center.

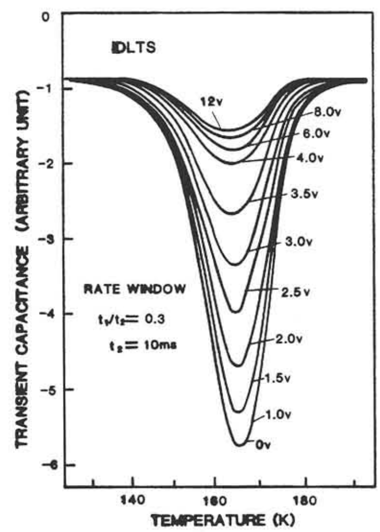

FIGURE 3. Typical IDLTS spectra with different base-collector reverse-bias pulse heights. The spectra were obtained with a given injection current density while the reverse-bias pulse is changed.

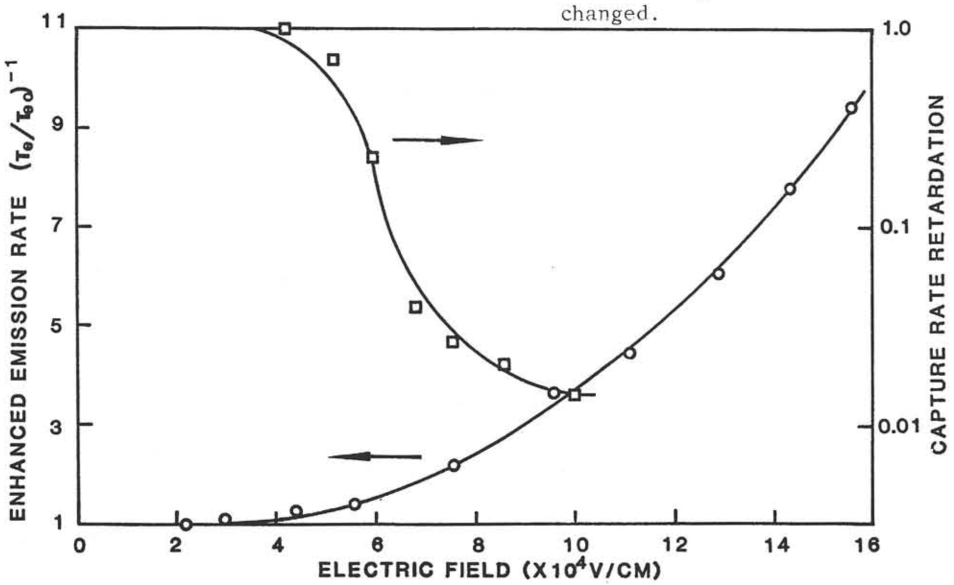

FIGURE 4. The enhanced emission and retarded capture rates for the E_V + 0.35 eV Au center as a function of electric field strength.