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Isothermal Capacitance Transient Spectroscopy

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A new measurement method for deep levels in semiconductors is demonstrated, by which the measurement of the transient change of capacitance is performed under an isothermal condition (Isothermal Capacitance Transient Spectroscopy). The method allows us to construct a precise measurement and analysis system by a programmable calculator. Detailed experiment and analysis by the method in the case of Au-doped Si in dicate that the method is one of useful tools for spectroscopic analysis of deep levels in semiconductors.

§1. Introduction

Extensive study of the nature of deep levels in semiconductors has been required in device technology. For example, more detailed knowledge of Au in Si is needed to control precisely the minority-carrier lifetime in Si pn junction devices and that of deep levels in laser-diode materials such as $Ga_{1-x}Al_xAs$ is also needed to preserve from the degradation. The TSC (Thermally Stimulated Current) method[1] or the DLTS (Deep Level Transient Spectroscopy) method[2] has been used as a spectroscopic tool for deep level analysis. However, it is difficult to measure the accurate temperature of the specimen in these spectroscopic methods, because the temperature of the specimen is continuously increased or decreased in these methods. Furthermore, it is not easy to construct a precise measurement and analysis system by a programmable calculator in these methods, accurate because digitizing and memorizing of the analog signals are difficult under the continuous thermal scan. In this report, a new measurement method for deep levels in semiconductors (ICTS, Isothermal Capacitance Transient Spectroscopy) is proposed,[3] by which the measurement of the transient change of capacitance is performed under an isothermal condition. The method allows us to construct a precise measurement and analysis system for deep levels in semiconductors.

§2. Principle of the Method

The ICTS method presented here is a variation of capacitance transient spectros-copy.[1] Under a dc reverse bias voltage V_R, the depletion layer capacitance C_0 of a p^+n junction is given as,[4]

$$C_0^2 = qk_s\varepsilon_0 A^2 N_{I0}/2(V_D + V_R), \qquad (1)$$

where q is the electronic charge, $k_s\varepsilon_0$ the dielectric constant, A the junction area, N_{I0} the net ionized impurity concentration in the depletion region, V_D the built-in potential. If $C(t)$ and $N_I(t)$ are the capacitance and the ionized impurity concentration, respectively, at time t after applying an injection pulse or a majority-carrier pulse, the relation between $C(t)$ and $N_I(t)$ is written as follows,

$$C(t)^2 = qk_s\varepsilon_0 A^2 N_I(t)/2(V_D + V_R). \qquad (2)$$

The change of the net ionized impurity concentration, $\Delta N_I(t) = N_I(t) - N_{I0}$, is given by the following equation, i.e.,

$$\Delta N_I(t) = \sum_i \Delta N_I^i(0) \exp\{-(e_n^i + e_p^i)t\}, \qquad (3)$$

where $\Delta N_I^i(0)$ is the increment of the concentration of filled ith level at $t=0$, e_n^i and e_p^i are the emission rates for electrons and holes at the ith deep impurity level, respectively. It is noted that $\Delta N_I^i(0)$ is a function of e_n^i and e_p^i.

From eqs. (1)–(3), we find the following relation,

$$f(t) = C^2(t) - C_0^2 = \sum_i B^i \exp(-t/\tau^i), \qquad (4)$$

where $B^i = qk_s\varepsilon_0 A^2 \Delta N_I^i(0)/2(V_D + V_R) = (\Delta N_I^i(0)/N_{I0})C_0^2$ and $\tau^i = (e_n^i + e_p^i)^{-1}$. Differentiating eq. (4) and multiplying the result by t, we obtain,

$$t\frac{df(t)}{dt} = \sum_i B^i(-t/\tau^i)\exp(-t/\tau^i). \qquad (5)$$

This equation indicates that $tdf(t)/dt$ has

a maximum value of $-B^i/e$ near $t=\tau^i$. Therefore, if we can obtain the function $t df(t)/dt$ from the transient capacitance measurement under an isothermal condition, the deep level parameters B^i and τ^i are given spectroscopically from the relation between $t df(t)/dt$ and t.

This basic idea of the ICTS is well understood by a simple simulation illustrated in Fig. 1. Figure 1(a) shows a relation $f(t)$ vs. t when two deep levels exist and their parameters B^i and τ^i are given as $B^I = 1$ F^2/cm^4, $B^{II} = 2$ F^2/cm^4, $\tau^I = 5 \times 10^{-7}$ sec and $\tau^{II} = 5 \times 10^{-5}$ sec. Figure 1(b) shows a relation $t df(t)/dt$ vs. $\log_{10} t$ for the same $f(t)$ as Fig. 1(a). As shown in the figure, two peaks appear corresponding to the time constant τ^I and τ^{II}, respectively. Values of them estimated from the peak points in the figure, are $B^I = 1.06$ F^2/cm^4, $B^{II} = 2.00$ F^2/cm^4, $\tau^I = 5.00 \times 10^{-7}$ sec and $\tau^{II} = 4.99 \times 10^{-5}$ sec, respectively. This result confirms the validity of the ICTS.

As B^i and τ^i are functions of e_p^i and e_n^i, the value of e_n^i or e_p^i, and the concentration of ith deep level can be determined from the values of B^i and τ^i. Further, the activation energy of e_n^i and e_p^i, and the deep level depth can be calculated by measuring B^i and τ^i at several isothermal conditions.

For example, in the case of $e_n \gg e_p$ (or $e_n \ll e_p$), we can readily obtain the trap density

Fig. 1. Computer simulations: (a) $f(t)$ vs. t curve. $f(t) = B^I \exp(-t/\tau^I) + B^{II} \exp(-t/\tau^{II})$, where $B^I = 1$ F^2/cm^4, $B^{II} = 2$ F^2/cm^4, $\tau^I = 5 \times 10^{-7}$ sec and $\tau^{II} = 5 \times 10^{-5}$ sec. (b) $t df(t)/dt$ vs. $\log_{10} t$ curve.

$N_T^i \simeq \Delta N_1^i(0) = B^i N_{I0}/C_0^2$ and $e_n \simeq (\tau^i)^{-1}$ (or $e_p \simeq (\tau^i)^{-1}$). Next, we consider a p$^+$n junction diode, in which only one deep acceptor level with the density of N_T exists in the n region and its e_n and e_p cannot be neglected. In this case, the net ionized impurity concentration (N_{I0}) in the depletion region under the dc reverse bias voltage is given by,

$$N_{I0} = N_D - \{e_p/(e_n + e_p)\} N_T, \qquad (6)$$

where N_D is the shallow donor density in the n region. Since N_{I0} is related with C_0 by eq. (1), N_{I0} can be determined by measuring C_0. On the other hand, the increment of the concentration of the filled deep acceptor level at $t = 0$ ($\Delta N_1(0)$) is given as

$$\Delta N_1(0) = \{e_n/(e_n + e_p)\} N_T, \qquad (7)$$

for the case of majority-carrier pulse application. From eqs. (6) and (7), $\tau = (e_n + e_p)^{-1}$ and $B = (\Delta N_1(0)/N_{I0})C_0^2$, we obtain the following equations,

$$N_T = N_D + (B/C_0^2 - 1)N_{I0}, \qquad (8)$$

$$e_n = (1/\tau)(B/C_0^2)(N_{I0}/N_T), \qquad (9)$$

and

$$e_p = (1/\tau)(N_D - N_{I0})/N_T. \qquad (10)$$

Then, we can determine N_T, e_n and e_p using eqs. (8)–(10) and measured quantities of τ, B, C_0 and N_{I0}.

In an actual measurement, we measure the transient change of capacitance $C(t)$ after applying an injection pulse or a majority-carrier pulse under an isothermal condition. Signals of $C(t)$ are converted to digital signals and memorized in a computer system and the relation between $t df(t)/dt$ and t is obtained by numerical calculation. Detailed analyses of B and τ are also performed by the same computer system.

§3. Experimental

In the ICTS method, $C(t)$ measurement should be done in the wide time range, if we want to get information of deep levels over a wide range of depths. Therefore, a capacitance meter and an A/D converter which can follow the fast variation of signal are required. In addition to these facilities, we must use a computer which can analyze the signal precisely and quickly.
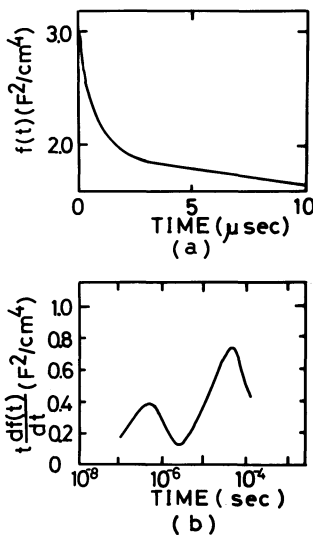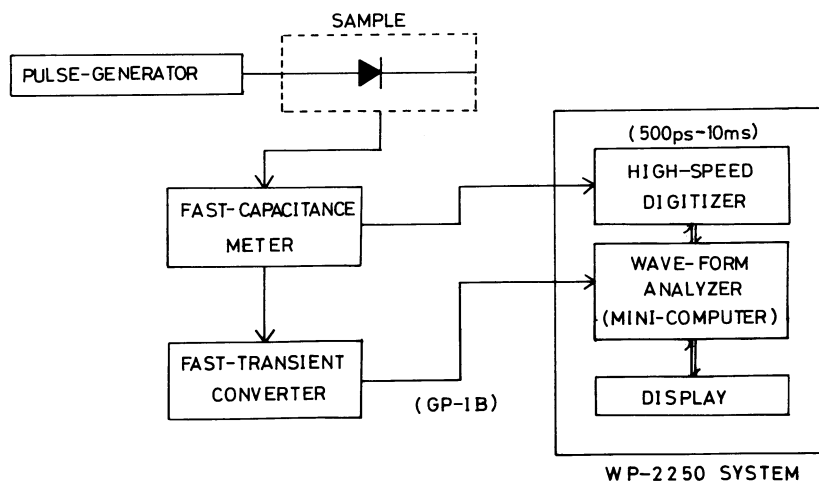
In our ICTS system, we have introduced a

Fig. 2. Block diagram of the ICTS system.

high-speed digitizer and waveform analyzer (Tektronix wp 2250 programmable digitizer system). Figure 2 shows a block diagram of the ICTS system. The capacitance meter (Sanwa MI-326, 20 MHz) can follow the variation of signal to about 1 μs and the high-speed digitizer can follow the time from 500 ps to 10 ms. For a long time range ($>$10 ms), a transient-converter is used, from which signals are transferred to the wp 2250 system through the GP–IB. In the experiment, we used only the wp 2250 system for data analysis.

The specimen used was a high-frequency rectifying Au-doped Si diode sold for practical use. In the measurement, the specimen was set in a cryostat (Oxford DN704) and the temperature of the specimen was controlled accurately by a controller (Oxford DTC-2).

§4. Results and Discussion

Figure 3 shows the ICTS signal (defined by $t\,\mathrm{d}f(t)/\mathrm{d}t$ vs. $\log_{10} t$) obtained in the case of majority-carrier pulse application under several isothermal conditions. As shown in the figure, only one negative peak (T_1) is obtained under an isothermal condition. T_1 is due to the Au-acceptor level. The peak position (corresponding to τ^i) moves towards a smaller value of $\log_{10} t$ with increasing temperature, while the peak height (corresponding to B^i/e) varies a little within the temperature range 290–327 K.

The ICTS signals in the case of minority-carrier pulse application are shown in Figs. 4 and 5.* In this case, two positive peaks (T_2 and T_3) and one negative peak (T_4) are ob-
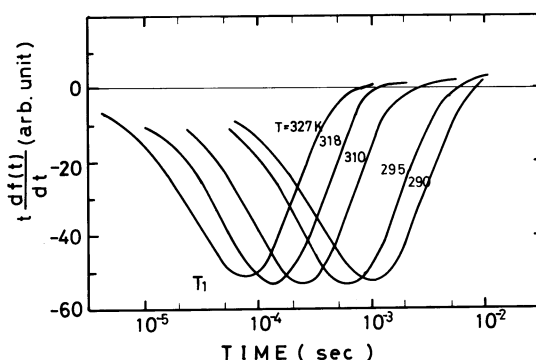

Fig. 3. ICTS signals ($t\,\mathrm{d}f(t)/\mathrm{d}t$ vs. $\log_{10} t$) obtained in the case of majority-carrier pulse application under several isothermal conditions.

tained. T_2 is due to the Au-donor level, T_4 due to the Au-acceptor level and T_3 due to a donor level whose origin is unknown.

The spectroscopical information of the ICTS is equivalent to that from DLTS measurement.[3] It should be, however, noted that the data analysis in the ICTS is simpler and more exact than that in the DLTS because the ICTS signal is based on $f(t) = C(t)^2 - C_0^2$ which is expressed as a summation of exponential functions (see eq. (2)), while the DLTS signal, strictly speaking, is based on non exponential

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*The observation of signals $T_2 \sim T_4$ at a temperature was impossible, because the wp 2250 system can measure the signal only in the range of 500 ps~10 ms. Therefore, the measurement was done at two temperature. However, if a transient-converter which can measure a long time range ($>$10 ms) is coupled with the wp 2250 system, all peaks will be observed at an appropriate temperature.
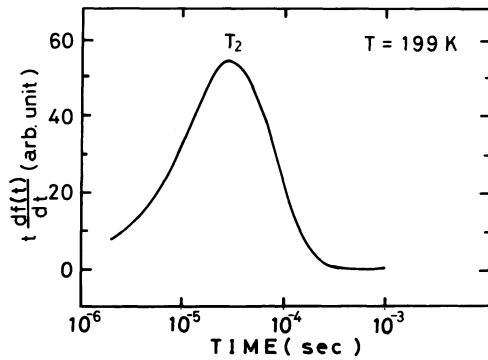
Fig. 4. ICTS signal in the case of minority-carrier pulse application at $T=199$ K.
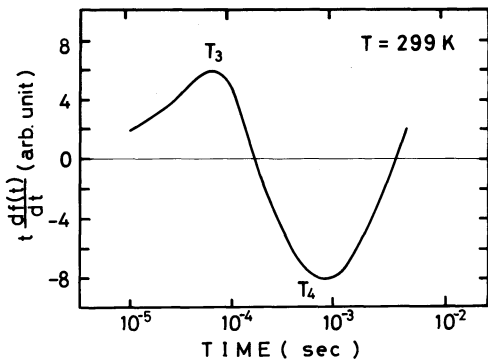

Fig. 5. ICTS signal in the case of minority-carrier pulse application at $T=299$ K.

function; $\Delta C(t) = C(t) - C_0$. It is noted that $\Delta C(t)$ becomes exponential function approximately in the case of $\Delta C/C_0 \ll 1$. The conventional DLTS method is applied to the case of $\Delta C/C_0 \ll 1$ to make analysis easy.

From the present experimental data, we can determine the concentration of Au and the emission rates of electron and hole for each Au level by using eqs. (8)–(10). For example, we obtained $N_{Au} = 6.97 \times 10^{13}/cm^3$ and the emission rates at the Au-acceptor level we obtained were $e_n = 1100$ s^{-1} and $e_p = 175$ s^{-1} at 295 K. Further, if we assume the following relation, i.e.,

$$e_n, e_p = A(T/300)^2 \exp(-\Delta E/kT), \quad (11)$$

where A is a constant and ΔE the effective energy depth. The values of A and ΔE for each emission rate are obtained as shown in Table I by using the measured values of e_n and e_p. In the table, the values of A and ΔE for each emission rate obtained by Sah et al.[5] are also

Table I. Numerical values of pre-exponential factor A and the effective energy level depth ΔE obtained by the present work and ref. 5.

	A(1/s)		ΔE(eV)	
	present work	ref. 5	present work	ref. 5
e_p^A	1.75×10^{12}	1.77×10^{12}	0.565	0.589
e_n^A	7.46×10^{11}	5.23×10^{11}	0.538	0.547
e_p^D	2.47×10^{13}	2.43×10^{13}	0.342	0.345

shown. The table shows that the results by the present work agree fairly well with those given in ref. 5.

§5. Conclusion

We have demonstrated a new measurement method for deep levels in semiconductors, i.e., the isothermal capacitance transient spectroscopy (ICTS). The method has the following advantages: (1) The information of deep levels is obtained spectroscopically. (2) The specimen temperature can be kept constant during the measurement, so the accurate specimen temperature can be measured easily. (3) As the measurement system is coupled with a programmable calculator, the precise experiment and analysis can be easily and quickly performed.

If we can use a capacitance meter with a sufficiently high response time and an analysis system which can measure the signal in a sufficiently wide time range, all signal peaks will be observed at room temperature.

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