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Isothermal Capacitance Transient Spectroscopy for Determination of Deep Level Parameters

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A new measurement method for deep levels in semiconductors is proposed, 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. Computer simulation and experiment by the method in the case of Au-doped Si are demonstrated. It is shown that the method is one of useful tools for spectroscopic analysis of deep levels in semiconductors.

§1. Introduction

Junction capacitance methods have been applied extensively to deep level studies in semiconductors.¹⁾ The introduction of the bias pulsing and the transient correlation (rate window) technique to the junction capacitance method has created a spectroscopic tool (Deep Level Transient Spectroscopy, DLTS)²⁾ for deep level analysis. Many reports have been published on the nature of deep levels in semiconductors studied by the DLTS or modulated DLTS methods.¹⁾ Further, some researchers have used a measurement system coupled with a programmable calculator.^{3,4)}

However, some difficult problems exist in the DLTS method. One of them is the accurate temperature measurement in the thermal scanning technique,¹⁾ with which temperature of the specimen is continuously increased or decreased. Accurate digitization and memorization of the analog signals are difficult under the continuous thermal scanning. Therefore, it is not easy to construct a precise measurement and analysis system by the programmable calculator in the DLTS method and it is difficult to take advantages of high-speed and simple signal processing techniques such as rate window technique in the DLTS method.

In this letter, a new measurement method for deep levels in semiconductors (Isothermal Capacitance Transient Spectroscopy, ICTS) is proposed, which removes the difficulties in the DLTS method mentioned above and allows us to construct a precise measurement and analysis system by a programmable calculator.

§2. Principle of the Method

The ICTS method presented here is a variation of capacitance transient spectroscopy.¹⁾ Under a dc reverse bias voltage V_R , the depletion layer capacitance C_0 of a p⁺n junction is given as,⁵⁾

$$C_0^2 = qk_s\epsilon_0 A^2 N_{10}/2(V_D + V_R), \quad (1)$$

where q is the electronic charge, $k_s\epsilon_0$ the dielectric constant, A the junction area, N_{10} the net ionized impurity concentration in the depletion region, V_D the built-in potential. If $C(t)$ and $N_1(t)$ 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 $N_1(t)$ is written as follows,

$$C(t)^2 = qk_s\epsilon_0 A^2 N_1(t)/2(V_D + V_R). \quad (2)$$

The change of the net ionized impurity concentration, $\Delta N_1(t) = N_1(t) - N_{10}$, is given by the following equation, i.e.,

$$\Delta N_1(t) = \sum_i \Delta N_1^i(0) \exp \{ -(e_n^i + e_p^i)t \}, \quad (3)$$

where $\Delta N_1^i(0)$ is the increment of the concentration of filled i th level at $t=0$, e_n^i and e_p^i are the emission rates for electrons and holes at the i th deep impurity level, respectively. It is noted that $\Delta N_1^i(0)$ is a function of e_n^i and e_p^i .

From eqs. (1), (2) and (3), we find the following relation,

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

where $B^i = qk_s\epsilon_0 A^2 \Delta N_1^i(0)/2(V_D + V_R)$ and $\tau^i =$

$(e_n^i + e_p^i)^{-1}$. Differentiating eq. (4) and multiplying the result by t , we obtain,

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

This equation indicates that $t df(t)/dt$ 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 . B^i and τ^i are functions of e_n^i and e_p^i . Therefore, e_n^i and e_p^i are determined uniquely from the values of B^i and τ^i . The concentration of i th deep level can be obtained from B^i . The deep level depth can be calculated by measuring τ^i at several temperatures.

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^i and τ^i are also performed by the same computer system.

§3. Simulation of ICTS

It is very instructive to make a simulation of the present ICTS method in the case of Au-doped Si and to compare with that of the DLTS method. The model used in the simulation is the same as that used successfully in the simulation of DLTS on Au-doped Si p^+n diodes.^{6)*} In Si, Au atom has two levels, namely, an acceptor level and a donor level.⁷⁾ Then, $\Delta N_i(t)$ can be given as

$$\Delta N_i(t) = (K^A - F^A) N_{Au} \exp\{-(e_n^A + e_p^A)t\} + (K^D - F^D) N_{Au} \exp\{-(e_n^D + e_p^D)t\}, \quad (6)$$

where

$$K^A = e_n^A / (e_n^A + e_p^A), \quad (7)$$

and

$$F^A = e_n^A \left/ \left[e_n^A + e_p^A (m_e/m_h)^{3/2} (p/n) g_n^A g_p^A \right] \right. \times \exp \left\{ \frac{E_g - 2(E_c - E_{Au}^A)}{kT} \right\}, \quad (8)$$

where m_e/m_h is the ratio of the effective mass of an electron to that of a hole, E_g the energy gap of Si, $g_n^A(g_p^A)$ the degeneracy factor of the Au acceptor level for electrons (holes), E_c the conduction band edge, E_{Au}^A the energy level of Au acceptor level, $n(p)$ the free electron (hole) concentration, k the Boltzmann constant and T the absolute temperature. Similar equations are given for K^D and F^D by changing the superscript A to D in eqs. (7) and (8). In the simulation, we used the following empirical relation about e_n and e_p for the two Au levels in Si obtained by Sah *et al.*,⁷⁾ i.e.,

$$e_n, e_p = A(T/300)^2 \exp(-\Delta E/kT), \quad (9)$$

where A is a constant, ΔE the effective energy level depth of the Au acceptor or the donor level. In Table I, the values of A and ΔE for each emission rate are given.⁷⁾ Using eqs. (5)–(8), the ICTS signal defined by $t df(t)/dt$ vs $\log_{10} t$ can be calculated using the values in Table I and $(m_e/m_h)^{3/2} = 0.4481$. Plotting $t df(t)/dt$ against $\log_{10} t$ has the advantage of providing directly the information of the deep level distribution in the energy gap.⁹⁾ The relation of $E_g = 1.193 - 2.42 \times 10^{-4} T$ (eV)⁸⁾ was used. We assumed $G = g_n^A g_p^A (p/n) = g_n^D g_p^D (p/n)$ and used it as a variable parameter.⁶⁾

Figure 1(a) shows the ICTS signal under the majority-carrier pulse application ($G=0$) at $T=300$ K. The negative peak due to the Au acceptor level is obtained at $t \approx 2 \times 10^{-3}$ s. Figure 1(b) shows the DLTS signal in the same majority-carrier pulse application at the rate window $t_1/t_2 = 50 \mu\text{s}/500 \mu\text{s}$. As shown in the figure, the ICTS signal corresponds to the DLTS signal. Both the ICTS and DLTS signals under the minority-carrier pulse application are shown in Fig. 2 ($G=64$). In these cases, two peaks correspond to the Au donor level and the Au acceptor level, respectively. These simulation results show that the information obtained from

Table I. Numerical values of pre-exponential factor A and the effective energy level depth ΔE used for the calculation.

Emission rate	A (1/s)	ΔE (eV)
e_n^A	1.77×10^{12}	0.547
e_p^A	5.23×10^{11}	0.589
e_n^D	6.77×10^{10}	0.771
e_p^D	2.43×10^{13}	0.345

*Y. Tokumaru and H. Okushi: Detailed analysis is preparing for publication.

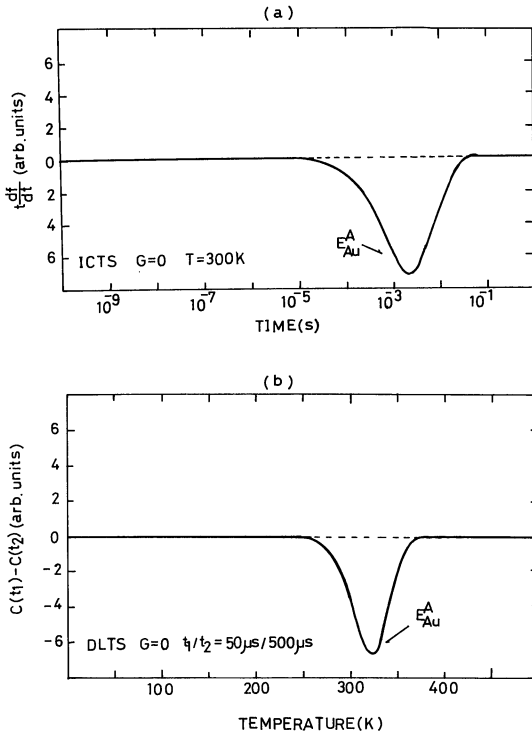


Fig. 1. Computer simulations: (a) ICTS signal for a Au-doped Si p^+n diode in the case of majority-carrier pulse application ($G=0$) at $T=300$ K. (b) DLTS signal corresponding to (a) at the rate window $t_1/t_2 = 50 \mu s/500 \mu s$.

the ICTS signal is equivalent to that from DLTS signal. Therefore, the present ICTS method is considered to become a spectroscopic tool for deep level measurement.

§4. Experiment

The most important problem in the present ICTS method is the measurement system. As shown in §3, if we want to get much information of deep levels, $C(t)$ measurement should be done in the wide time range (for example, a range of $10^{-6} \sim 10^2$ s is required). Therefore, a fast capacitancemeter and a fast A/D converter are required in the ICTS method.

Figure 3 shows a block diagram of our ICTS system used in the present experiment. The fast capacitancemeter (Sanwa MI-326, 20 MHz) can follow the variation of signal to about $1 \mu s$ and the transient converter (A/D converter) (Riken Denshi TCED-4000) can also follow to $1 \mu s$. An HP 9825A calculator and an HP 7245A plotter/printer are used.

The specimen used in the experiment was

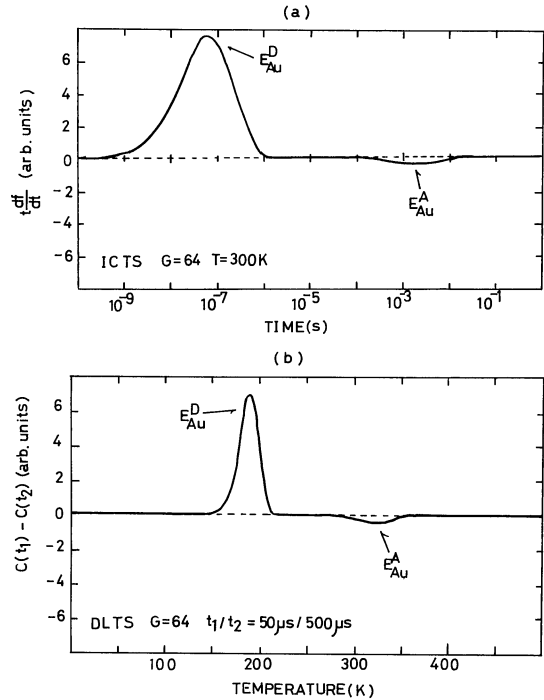


Fig. 2. Computer simulations: (a) ICTS signal for a Au-doped Si p^+n diode in the case of minority-carrier pulse application ($G=64$) at $T=300$ K. (b) DLTS signal corresponding to (a) at the rate window $t_1/t_2 = 50 \mu s/500 \mu s$.

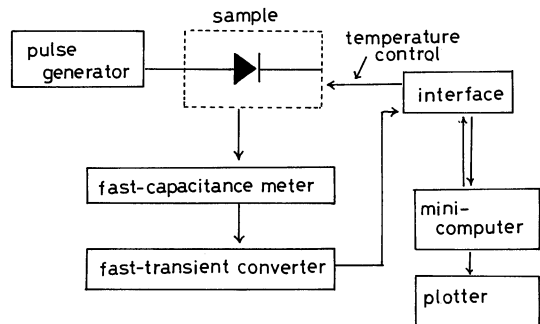


Fig. 3. A block diagram of the ICTS system used in the present experiment.

fabricated from Au-diffused Si p^+n junction wafers whose N_D in the n region was $2 \times 10^{15} \text{ cm}^{-3}$. Figure 4 shows a typical ICTS signal obtained experimentally in the case of majority-carrier pulse application. This result is in good agreement with that of the simulation described in §3. The Au concentration and acceptor level depth determined by our ICTS are $6.5 \times 10^{14} \text{ cm}^{-3}$ and 0.57 eV , respectively. These values agree fairly well with those by the DLTS within the experimental errors ($\pm 1 \times 10^{14} \text{ cm}^{-3}$,

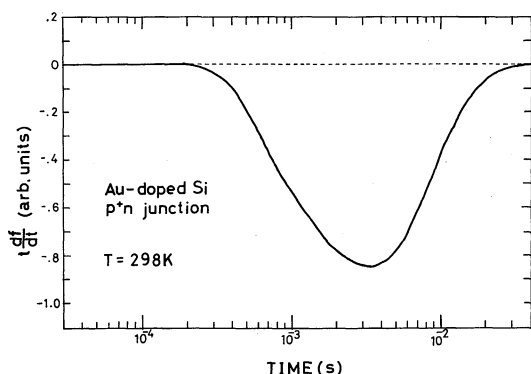


Fig. 4. ICTS signal obtained experimentally for a Au-doped Si p⁺n diode in the case of majority-carrier pulse application (pulse width=10 μ s) at T=298 K.

± 0.03 eV).

§5. Concluding Remarks

The basic idea of isothermal capacitance transient spectroscopy (ICTS) is presented and its computer simulation and experiment are demonstrated. We consider that the ICTS method will become one of useful tools for spectroscopic analysis of deep levels in semiconductors. We believe that the ICTS method will be improved by introducing recently developed

apparatus such as high-speed digitizer and waveform analyzer.

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