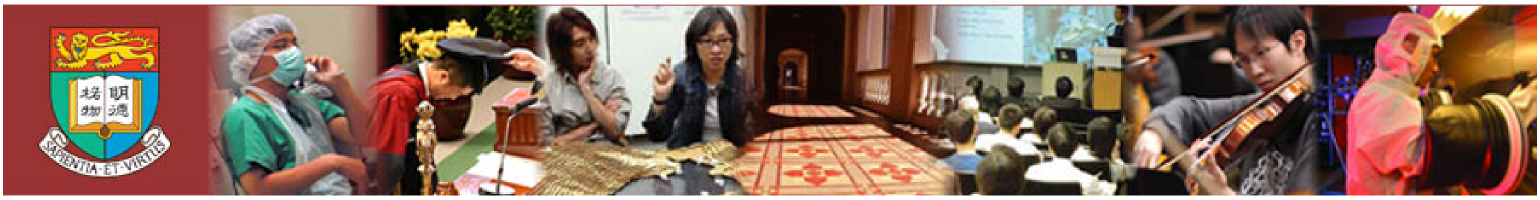

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Application of positron annihilation lifetime technique to the study of deep level transients in semiconductors

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Unlike its conventional applications in lattice defect characterization, positron annihilation lifetime technique was applied to study temperature-dependent deep level transients in semiconductors. Defect levels in the band gap can be determined as they are determined by conventional deep level transient spectroscopy (DLTS) studies. The promising advantage of this application of positron annihilation over the conventional DLTS is that it could further extract extra microstructure information of deep-level defects, such as whether a deep level defect is vacancy related or not. A demonstration of EL2 defect level transient study in GaAs was shown and the EL2 level of 0.82±0.02 eV was obtained by a standard Arrhenius analysis, similar to that in conventional DLTS studies. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1436551]

As lattice defects play important roles in the performance of semiconductor materials, many spectroscopies were used to characterize those defects. Among them, deep level transient spectroscopy (DLTS) is effectively used to determine the energy levels of defects in band gaps. However, it could not directly extract microstructure information of the defects.

As an antiparticle of the electron, the positron is sensitive to electrical potential of point defects and has proved to be a valuable nondestructive probe for vacancy-type defects.[1] The positron annihilation lifetime (PAL) spectroscopy has conventionally been used to obtain microscopic information of defects, such as defect size, charge states, and defect concentration. During the past decade, PAL has been intensively applied to characterize defects in various semiconductors.[2]

Unlike its conventional role in the field of defect study, we demonstrated here that an application of PAL can be developed to study the transients of defect deep levels in the band gap of semiconductors. The basic principle is that positrons are used as an electric field sensor inside the depletion region, where the transients of defect charge states due to carrier emission or capture cause the change of the electric field. Positrons can be drifted to the metal–semiconductor interface of the Schottky junction within the annihilation time of the particle. The intensity of the interface positron lifetime component and average lifetime can thus be used to monitor the transients of electric field in the depletion region, whereas in conventional DLTS, the variation of depletion region capacitance is monitored to show the transients of deep levels.

In this work, the application of PAL was demonstrated to study the defect level transients in the temperature range of 15–300 K in GaAs. Deep level peaks of EL2, and possible EL6 were observed.

Two identical pieces of semiconductor sample were prepared and metal–semiconductor Schottky contacts were made on one side of each sample. A 5μCi point positron source of ^{22}Na were then sandwiched by the two wafer samples with metal contacts facing each other so that incident positrons would first get through the surface metal layer and then are implanted into the depletion region of the Schottky contact. Square wave biases were applied to the samples so that the positron injecting Schottky contacts were reversed biased during one half of the cycle and forward biased during the other half of the cycle.

During the period of reverse bias (ionization cycle), defect levels inside the depletion region will ionize and form a higher density space-charge region with a stronger electric field pointing backward to the positron injecting contacts. More implanted positrons will then be drifted back toward the metal contacts. During the period of forward bias (neutralization cycle), ionized defect levels inside the depletion region will be neutralized and reducing the density of space-charge and the electric field. Less positrons will be drifted backward to the positron injecting metal contacts. Thus the drift of positrons will directly reflect the ionization of defect levels.

A standard positron lifetime spectrometer was used to collect the positron lifetime spectra featuring the effects of positron drifting to metal–semiconductor interface. A synchronized gating logic pulse from the square wave generator allowed lifetime spectra to be collected in coincidence with the reverse biased ionization cycle.

In this work, undoped liquid encapsulated Czochralski grown semi-insulating GaAs sample were used to show the feasibility of this new application of PAL. The free-carrier, EL2, and C concentrations of the sample were 6×10^7, 1.5×10^{16}, and 1×10^{15} cm^{-3}, respectively. Metal contacts (Au) were thermally evaporated onto the sample surfaces with thickness of 1000 Å. The measurements were carried out at the temperature range of 15–300 K, with the frequency range of the applied square wave pulse from 1 mHz to 1 kHz. Each lifetime spectra contained 2×10^6 counts.

Figure 1(a) shows the average positron lifetime as the function of the frequency of applied square wave bias at different temperatures. The lifetime spectra were collected

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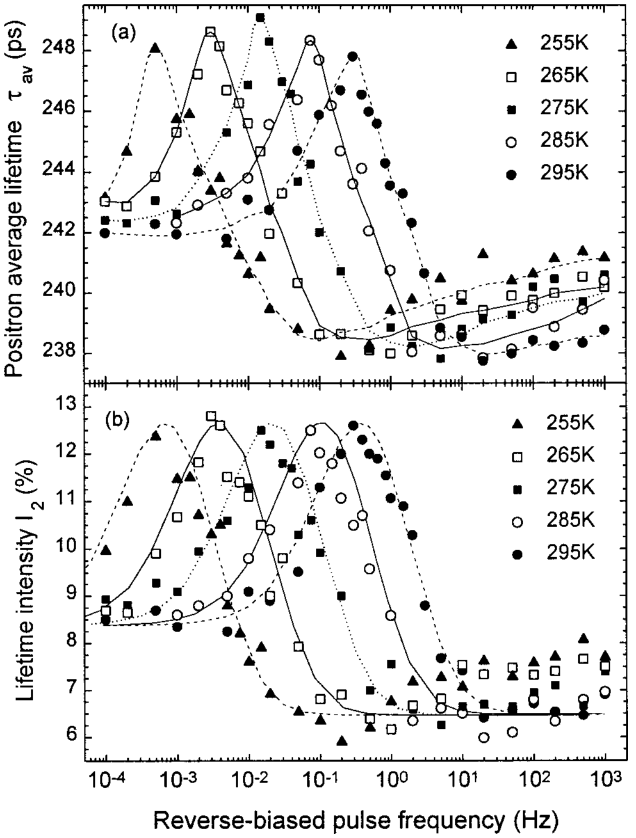

FIG. 1. (a) The pulse frequency dependence of average positron lifetime τ_{av} for Au/GaAs at different temperatures. (b) The pulse frequency dependence of Au/GaAs interface positron lifetime intensity I_2 at different temperatures.

during the half cycles of the square wave, during which the positron incident Schottky contact was reversed bias, so that the deep levels in the depletion region undergo an ionization process.

It was observed that τ_{av} increases as the frequency increases at low frequency range and reached its peak value of around 248 ps. The peak value was nearly temperature independent, and the peak positions, however, were sensitive to the temperature. When the frequency further increases, τ_{av} began to decrease from its peak value to about 238 ps and saturated around this value. This phenomenon can generally be explained using the model proposed in our earlier study[3]. It is well known that τ_{av} is basically the combination of multipositron lifetime components and those components are spatially dependent when positrons were drifted under the action of the electric field. In this case, positrons were drifted from the bulk region back to the Au/GaAs interface by the strong electric field in the depletion region. Therefore, τ_{av} depended strongly on the fraction of positrons backdrifted to the interface, relevant to the Au/GaAs interface I_2, and the interface lifetime τ_2. It has been observed that τ_2 is around 400 ps, a typical value of positron annihilation at microvoids.[3]

The fraction of positron backdrift to the interface depends on the transients of electric field, or the frequency of the reverse biased pulse causing the transients of defect ionization. Thus the variation of τ_{av} reflects the variation of I_2, and consequently the transient of electric field or the transient of EL2.

I_2 was obtained from the spectrum decomposition. Since τ_2 of 400 ps is the characteristic Au/GaAs interface microvoids, which are quite stable over a large temperature range,[4] only a few ps variation of τ_2 was observed due to lattice thermal expansion and no obvious frequency dependence of τ_2 was observed. Therefore τ_2 was fixed at 400 ps during the spectrum decomposition. The frequency dependence of I_2 at different temperatures was shown in Fig. 1(b). The I_2 data can be understood using the earlier proposed model.[3] At high frequencies, there is insufficient time for the defect level to be ionized and thus negligible space-charge density forms. Positrons experienced weak back drifting electric field and a relatively low I_2 value was observed. As the frequency decreased, space charge of ionized deep donors and the accompanying electric field begins to become appreciable within the emission half cycle leading to larger I_2 values. The I_2 peak results from the following competition process. As the electric field increases, which is favorable for the increase of I_2, the width of the depletion region decreases, which leads to a smaller fraction $[\sim(1\text{-}e^{-\alpha w})]$ of implanted positions being within the strong field of the depletion region, favoring the decrease of I_2. There is thus some optimal frequency of the bias pulse at certain temperatures for which positrons backdrifted to the interface are maximized.

The solid lines in Fig. 1(b) are the fittings of numerical calculation to the experimental data at various temperatures, showing the basic correctness of the model. The energy level of 0.81±0.03 eV was obtained from the fits. Although the theoretical fitting could explain the data reasonably well, uncertainties of the energy level determination could be caused because multiparameters were involved during the fitting process.

In comparison with the conventional DLTS more directly, temperature scans of I_2 in the range of 15–300 K with different pulse frequencies (corresponding to the rate windows in DLTS) were carried out and shown in Fig. 2. Similar to the DLTS signal peaks of $\Delta C(T)$, the $I_2(T)$ curves, featured by defect level peaks, were observed by this positron-lifetime DLTS method. In addition to the deep defect EL2 peak at higher temperatures (above 250 K), a shallower defect peak (possibly EL6) might also exist at low temperatures (below 150 K). Because of the low concentration of the possible shallow defect, the correspond I_2 peaks could not be observed with the error up to ±0.5% when I_2 values are low. Further studies are being carried out on samples with higher defect concentrations to identify this possible shallow defect.

As known in conventional DLTS, the peak emission rate $e_n(T_p)$ of a DLTS signal peak at temperature T_p, can be determined by the selected rate windows of t_2/t_1 through $e_n(T_p)=\ln[(t_2/t_1)/(t_2-t_1)]$. Meanwhile,

$$k_B \ln \frac{e_n(T_P)}{T_P^2} = -(E_C - E_T)\cdot\frac{1}{T_P} + \ln e_{n0}. \quad (1)$$

Thus the energy level of deep defect E_T can be obtained by means of a standard Arrhenius analysis, i.e., plotting the lin

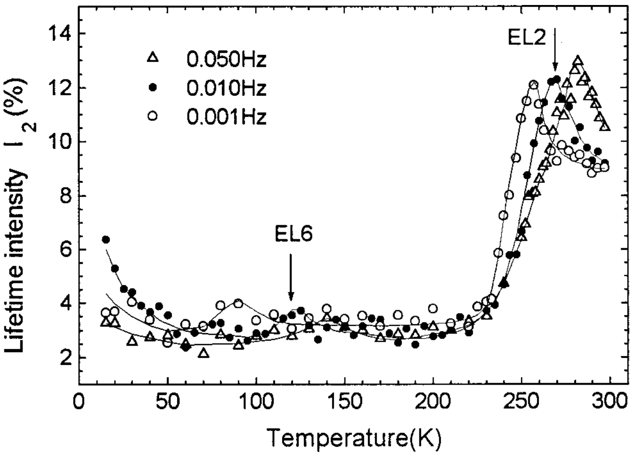

FIG. 2. The temperature dependence of the Au/GaAs interface positron lifetime intensity I_2 for different filling pulses.

ear relationship between $k_B \ln[e_n(T_P)/T_P^2]$ and $1/T_P$. The slope of the line gives the position of the energy level.

A similar methodology was suggested and could be employed to the present study to find the trap energy level.[5] Unlike in conventional DLTS, the electrical signal (capacitance) and consequently the trap emission rate at each temperature can be measured instantly, PLT spectra here are accumulated during the whole time of the emission half period τ. The measured interfacial intensity I_2 is the time averaged $i_2(t)$ during the emission half period, i.e.,

$$I_2 = \int_0^{\tau} i_2(t)dt/\tau = \int_0^1 i_2(\tau t')dt'. \tag{2}$$

The instant $i_2(t)$ is the function of the ionized concentration of defect level, $N_+(t)$, i.e.,

$$I_2 = \int_0^1 f[N_+(\tau t')]dt' = \int_0^1 f[N_+(\phi,t')]dt'. \tag{3}$$

Thus providing the scaled emission rate $\phi = e_n(T)\tau$ is held constant by suitable adjustment of $e_n(T)$ and τ, then the same values of I_2 result. In other words, for I_2 peaks in Figs. 1(b) and Fig. 2 observed at temperatures T_p and frequencies (π/τ_p), the peak scaled emission rate ϕ_p, which is the product of the emission rates $e_n(T_p)$ and the τ_p should be same

$$\phi_p = e_n(T_p)\tau_p = e_{n0}T_p^2 \exp\left(-\frac{E_C - E_T}{k_B T_p}\right)\cdot \tau_p, \tag{4}$$

$$k_B \ln \frac{\tau_p^{-1}}{T_p^2} = -(E_C - E_T)\cdot \frac{1}{T_p} + \ln \frac{e_{n0}}{\phi_p}. \tag{5}$$

Thus the energy level of deep defect can be obtained by means of plotting $k_B \ln(\tau_m^{-1}/T_m^2)$ against $1/T_m$. The slope of the line gives the energy level. Figure 3 shows the Arrhenius plots for those I_2 peaks. From Fig. 1(b), the energy level of $E_C - E_T = 0.79 \pm 0.03$ eV was obtained, which is the typical EL2 defect. From Fig. 2, the energy level of EL2 of 0.82 ±0.02 eV was obtained. Both the above obtained values of EL2 deep level by the positron DLTS method are in good agreement with the EL2 level of 0.81–0.83 eV.[6,7]

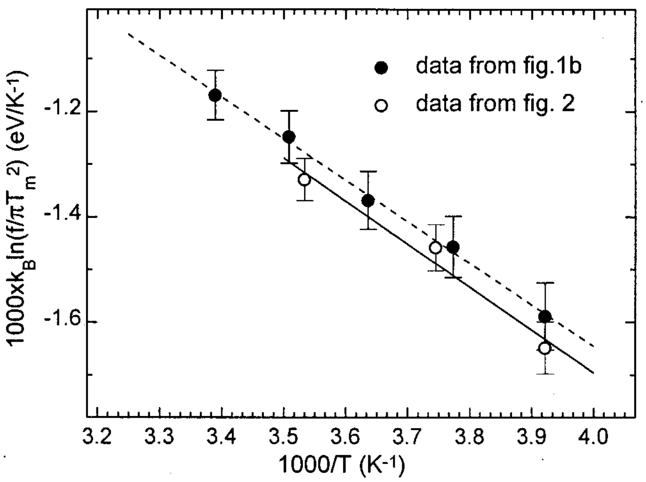

FIG. 3. The positron DLTS Arrhenius plots for EL2 deep level in GaAs, obtained by the peak positions of Figs. 1(b), and 2, respectively.

In summary, this work has demonstrated that the type of information available using a conventional DLTS technique, such as trap energies and cross section, can be obtained to a reasonable degree of accuracy by monitoring the transient electric fields in the depletion region of a semiconductor by way of positron drift to an interface. The fact that the positron can respond to electric-field transients occurring down to the nanosecond time range (because of its short lifetime ~0.2 ns in semiconductors) could also lend an advantage over capacitance transient measurements, since the latter cannot be effectively measured at submillisecond times. Such fast measurements of electric-field transients would mean that in the future trap levels occurring much closer to the conduction and valence bands could become accessible at liquid-nitrogen temperatures and above using similar positron annihilation techniques.

In addition to its conventional application in the characterization of defect microstructures and charge states, it is demonstrated that the PLT technique can be employed to study temperature dependent defect transients in semiconductors. The promising advantage of this technique over the conventional DLTS is that it can be further developed to offer microscopic information of defects, as well as their electronic characters.

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