Multiple Non-exponential Decay of Photo-induced Excess Electrons in Heterostructures *

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The derivative $-dN(t)/d\lg t$ of photo-induced excess electrons $N(t)$ in GaAs-$Al_{0.3}Ga_{0.7}As$ and $In_{0.15}Ga_{0.85}As$-$Al_{0.2}Ga_{0.8}As$ heterostructures with respect to $\lg t$ shows a spectrum with pronounced peak-structure. The apparent capture energies, the lifetime prefactors, the apparent lifetime distribution, and the derivative decay quantities of individual lifetimes were analyzed to distinguish capture mechanisms.

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Unlike the exponential decay, the multiple non-exponential decay of photo-induced excess electrons $N(t)$ in heterostructures has an apparent distribution of lifetimes, and the form of the distribution is generally unknown.[1,2,5] In cases with narrow distribution of lifetimes, the decay may fit the Williams-Watts or "stretched exponential" form $N(t) = N_{00} + N_0 \exp[(-t/\tau)\beta]$, where N_{00} is the decay baseline, N_0 is the decay amplitude, and τ is the single lifetime.[2-4] The physical meaning of β is not yet clear.[2,3] In other cases, the multiple non-exponential decay does not fit the Williams-Watts form.[1,5,6]

A logarithmic derivative method[5,6] was introduced to analyze the multiple non-exponential decay. The negative $\lg t$ derivative of the carrier number density $N(t)$, that is $K = -\mathrm{d}N/\mathrm{d}\lg t$, was calculated and plotted with respect to $\lg t$. By using formula $\ln\tau(T) = \ln\tau_0 + E_c/(kT)$, the temperature dependence of the spectra was analyzed to yield the apparent capture energies E_c and the corresponding lifetime prefactors τ_0. The macroscopic barrier tunneling related persistent photoconductivity (PPC) decay with long lifetime prefactor ($\tau_0 > 10^{-9}$ s) was distinguished from the direct microscopic DX-center capture ($\tau_0 = 10^{-12}$ s) in temperatures range of $60 < T < 180$ K.[5] A phonon-assisted tunneling model with a maximum relaxation of the tunneling electrons results in various values of E_c. With temperatures from low to high, E_c vary from the direct capture energy value of 200 meV with long τ_0 (10^{-3}–10^{-10} s) to the value as high as 400 meV with short $\tau_0 = 10^{-12}$ s.[6] A later study including smaller relaxation of the tunneling electrons agrees with the experimental value of E_c as low as 70 meV at $70 < T < 100$K.[7] However the general analysis of the lifetime distribution of the spectrum was not explored, which may play an important role in distinguishing different capture mechanisms.

For an exponential decay $N = N_{00} + N_0 \exp(-t/\tau)$, $K = (t/\tau)(\ln 10)N_0 \exp(-t/\tau)$. Plotted with respect to $\lg t$ axis, the derivative is strongly peaked at precisely $\lg\tau$ with a peak value of $0.847N_0$ as shown a dashed curve in Fig. 1 with $\lg\tau = 0$, as well as in Fig. 2 with $\lg\tau = 0.5$.

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The full width at the half maximum (FWHM) of any single decay peak is a constant about 1.05, and the area beneath the peak is exactly N_0. For the case of multiple-rate decay with the form of $N(t) = \Sigma_i N_{0i} \exp(-t/\tau_i)$, $K = \Sigma_i (t/\tau_i)(\ln 10) N_{0i} \exp(-t\tau_i)$, where subscript i is corresponding to different decay rate. The $\lg t$ derivative is the superposition of the individual exponential decays. The distribution of N_{0i} with respect to capture energy[2,7] can be exponential or Gaussian. In formula $\ln\tau_i = \ln\tau_0 + E_c/(kT_i)$, the lifetime prefactor τ_0 is considered as a constant. The capture energy is linear to $\lg\tau_i$. Therefore we may also assume a similar distribution form: $N_{0i} \propto \exp[-(|\lg\tau_i - \lg\tau_{\text{center}}|/\Delta)^n]$, Δ is the distribution width in $\lg t$. When $n = 1$, the distribution is exponential. When $n = 2$, it is Gaussian. In the case of exponential distribution, the solid curves in Fig. 1 show five broadened peaks with $\Delta = 0.5, 1.0, 1.5, 2.0,$ and 2.5. Their FWHM are 1.65, 2.3, 3.0, 3.65, and 4.35 respectively. The FWHM of the peaks are linear to Δ in a wide range of $1.05 < \text{FWHM} < 7.1$ and $0.1 < \Delta < 4.5$. The calculation for the case of Gaussian distribution shows similar results in a wide range of $1.35 < \text{FWHM} < 8.2$ and $0.5 < \Delta < 5.0$.

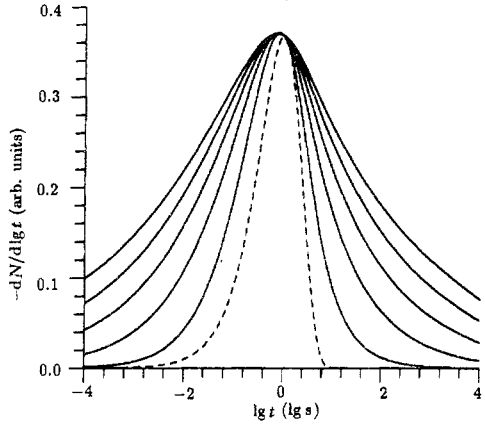

Fig. 1. Spectra of different distribution.

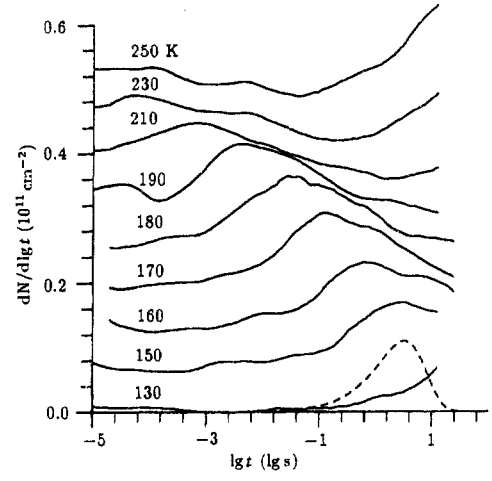

Fig. 2. HEMT sample at $T = 130 - 250$ K.

The experiments in this work are the transient Hall measurements on photo-induced excess electrons in heterostructures. The material was grown by molecular beam epitaxy. For the high electron mobility transistor (HEMT) sample, the thick undoped GaAs substrate was followed by an undoped $Al_{0.3}Ga_{0.7}As$ spacer layer (3 nm). It is then followed by $Al_{0.3}Ga_{0.7}As$ of 50 nm with 1×10^{18} cm^{-3} silicon and GaAs cap layer of 10 nm with 3×10^{18} cm^{-3} silicon. For the pseudomorphic-HEMT (P-HEMT) sample, the thick undoped GaAs layer was followed by an undoped $In_{0.15}Ga_{0.85}As$ layer, and then an undoped spacer layer (3 nm) of $Al_{0.2}Ga_{0.8}As$. It is then followed by $Al_{0.2}Ga_{0.8}As$ of 50 nm with 1×10^{18} cm^{-3} silicon and GaAs cap layer of 10 nm with 3×10^{18} cm^{-3} silicon. A light pulse of 10^{-4} s was emitted from a infrared light emitting diode of 940 nm near the samples.

Figure 2 shows the logarithmic derivative spectra of the HEMT sample. The temperatures are 130, 150, 160, 170, 180, 190, 210, 230, and 250 K respectively. To obtain a better picture to see the evolution of the spectra, the spectra of 150, 160, 170, 180, 190, 210,

230, and 250 K are displaced and shifted up by 0.06, 0.12, 0.18, 0.24, 0.30, 0.36, 0.42, and $0.48 \times 10^{11}\,\mathrm{cm}^{-2}$ respectively. A pronounced peak shifts to the left with increasing temperatures from 150 to 210 K. The peak broadening is obvious. The FWHM of the main peak of each complete spectrum is 2.3 ± 0.3, which is much larger than the FWHM of the spectrum of the single decay (FWHM = 1.05). From the horizontal shift of the peaks with different temperatures, the apparent capture energy is 400 ± 30 meV. The lifetime prefactor is 10^{-12} s. Such apparent capture energy in this range of temperatures indicates a phonon-assisted tunneling of photoelectrons from the GaAs-$Al_{0.3}Ga_{0.7}As$ interface into the DX-centers in Si-doped $Al_{0.3}Ga_{0.7}As$ layer with a maximum relaxation of the tunneling electrons.[6] By formulas $K = \Sigma_i (t/\tau_i)(\ln 10) N_{0i} \exp(-t/\tau_i)$ and $N_{0i} \propto \exp[-(|\lg \tau_i - \lg \tau_{\mathrm{center}}|/\Delta)^n]$, one-peak fitting results in $\Delta = 1.0 \pm 0.2$. One-peak fitting on the data of direct capture into DX-centers[2] results in $\Delta = 1.6 \pm 0.4$. From the data of a phonon-assisted tunneling with small relaxation of the tunneling electrons,[7] we have $\Delta = 1.2 \pm 0.3$. The broadening was attributed to the capture barrier distribution of the DX-center in Si-doped $Al_xGa_{1-x}As$ layer. Above data are from the HEMT samples with aluminum fraction $x = 0.30$–0.35. Their Δ values are about the same although E_c or τ_0 are quite different. Therefore the FWHM value extracted from the spectrum peaks could be also an evidence to analyze the capture mechanisms.

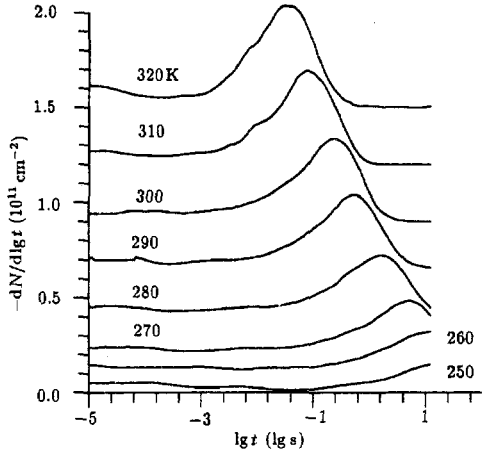

Fig. 3. HEMT sample at $T = 250 - 320$ K.

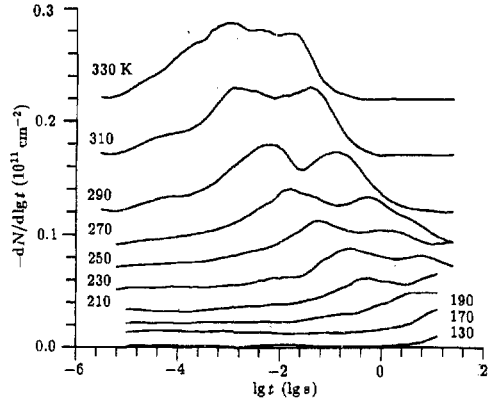

Fig. 4. P-HEMT sample at $T = 130 - 330$K.

Figure 3 shows the spectra of the same HEMT sample at temperatures of 250, 260, 270, 280, 290, 300, 310, and 320 K respectively. For the same reason as in Fig. 2, the spectra of 260, 270, 280, 290, 300, 310, and 320 K are displaced and shifted up by 0.1, 0.2, 0.4, 0.65, 0.9, 1.2, and $1.5 \times 10^{11}\,\mathrm{cm}^{-2}$ respectively. At the temperatures of 210, 230, and 250 K in Fig. 2, a new peak seems to shift from the right side to the left. This peak becomes so pronounced in Fig. 3 from 270 to 320 K. Unlike the spectra in Fig. 2, the FWHM of the new peak from each complete spectrum in Fig. 3 is about 1.3, which is only slightly larger than the FWHM of the single decay spectrum. The value of E_c is 740 ± 50 meV with $\tau_0 = 10^{-13}$ s. Obviously, the value of E_c is too large to fit the DX-center related capture mechanisms. One-peak fitting on the data results in $\Delta = 0.20 \pm 0.04$, which is much smaller than that of the data from Fig. 2.

This small value of Δ also indicates new capture centers totally different from the DX-centers.

Figure 4 shows spectra of the multiple non-exponential decay from the $In_{0.15}Ga_{0.85}As$-$Al_{0.2}Ga_{0.8}As$ P-HEMT sample. The temperatures are 130, 170, 190, 210, 230, 250, 270, 290, 310, and 330 K. The spectra of 170, 190, 210, 230, 250, 270, 290, 310, and 330 K are displaced and shifted up by 0.01, 0.02, 0.03 0.05, 0.07, 0.09, 0.12, 0.17, and $0.19 \times 10^{11}\,cm^{-2}$ respectively. The experimental spectra of $T > 220$ K show strongly a two-peak structure with a total FWHM about 3.5. A two-peak fitting shows that the left peak has $\Delta = 0.4 \pm 0.1$, while the right peak has $\Delta = 0.3 \pm 0.1$. These values of FWHM are closer to the FWHM values of the peaks in Fig. 3 but far from the FWHM values of the peaks in Fig. 2. There is no evidence of the DX-center related capture in Fig. 4 with $150 < T < 210$ K. The experimental spectra of $T < 150$ K show only very small logarithmic derivative value of the decay. These agree with the conclusion that the PPC effect in $Al_xGa_{1-x}As$ is very weak when the aluminum fraction $x < 0.23$.[8] In Fig. 4 with $210 < T < 330$ K, the horizontal shift of the spectra with different temperatures is obvious. The E_c of the left peak of the two-peak structure is 380 ± 30 meV with τ_0 of 10^{-9} s. The E_c of the right peak is 400 ± 30 meV with $\tau_0 = 10^{-8}$ s. The longer lifetime prefactors in this P-HEMT sample indicate that the tunneling is involved in this case. Unknown capture centers should be in the AlGaAs layer after the tunneling barrier. Experiment shows the P-HEMT sample has much smaller electron number density at the interface ($N_s = 5 \times 10^{11}\,cm^{-2}$) than that of the HEMT sample ($N_s = 15 \times 10^{11}\,cm^{-2}$). Smaller N_s also indicates extra capture centers in the AlGaAs layer.

The closer values of FWHM from HEMT and P-HEMT samples at $210 < T < 330$ K indicate a similar FWHM broadening mechanism. However, the origin of differences in FWHM from different samples is not yet clear. More work needs to be done to have more precise pictures of the capture mechanisms.

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