Photoinduced recovery of photoquenched hopping conduction in neutron-irradiated semi-insulating GaAs

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The photoinduced recovery that starts from the full quenched state in tunneling-assisted hopping conduction has been observed in neutron-irradiated semi-insulating GaAs preilluminated with laser-diode light of 1410-nm wavelength. This recovery phenomenon supports the interpretation that the *EL*2-like defects created by thermal annealing at around 250 °C after neutron irradiation are to be identified as the native *EL*2 defect. According to the photoresponse study using different wavelengths, neutron-induced *EL*2 defects are likely to have several quenchable components.

The photoquenching phenomena[1,2] of hopping conduction has been found in neutron-irradiated semi-insulating (SI) GaAs preilluminated using light-emitting diodes (LED) with various peak wavelengths of 850 nm (photon energy 1.46 eV), 890 nm (1.39 eV), and 940 nm (1.31 eV). This phenomenon originates from the transformation from the normal state to the metastable configuration of the hopping sites consisting of the midgap electron traps (*EL*2 or *EL*2-like defect), which are created by thermal annealing at around 250 °C after neutron irradiation. On the other hand, high-dose neutron irradiation destroys completely the atomic structure of *EL*2,[1,3] accompanied by the hopping conduction without photoquenching. It is an important problem as to whether or not the neutron-induced quenchable component is to be identified as a native *EL*2 defect.[4] It is therefore interesting to observe the photoinduced recovery[5] of the quenchable component as found for the native *EL*2 defect. Studying the detailed characteristics of the hopping sites would provide another approach to the constitution of an atomic model of the *EL*2 defect.

In this paper, we report the photoinduced recovery of the tunneling-assisted hopping conduction photoquenched in neutron-irradiated SI GaAs. According to the photoresponse of the quenchable component in the hopping conduction, the neutron-induced *EL*2-like defect is likely to be identified as the native *EL*2 defect.

The crystals used in this study were undoped SI GaAs ($\rho \sim 2\times10^7$ Ω cm) grown by the liquid-encapsulated Czochralski technique. The as-grown crystal contains *EL*2 defects of $\sim 1.2\times10^{16}$ cm^{-3} concentration. Neutron irradiations were performed using the Kyoto University Reactor (KUR), which is a light-water-moderated research reactor. Samples were irradiated with fast (fluence equals 3.7×10^{18} cm^{-2}) and thermal neutrons (1.3×10^{19} cm^{-2}) at fluxes of 1.4×10^{13} and 4.7×10^{13} cm^{-2} sec^{-1} for each neutron. Ohmic contacts with a gap of 1 mm were fabricated by sintering the Au-Ge-Ni alloy for 1 min at 480 °C. A typical sample dimension was $2\times5\times0.2$ mm^3. The effective illumination area was 2×1 mm^2. Conductance measurements were carried out at a temperature ranging from 80 to 300 K in the dark before and after the illumination of the quenching light using an electrometer (Keithley 617). Since the maximum photoinduced recovery for the photoquenched *EL*2 defect occurs approximately in the 0.85–0.95-eV range,[6] the photoquenching and recovery were performed using a $Ga_xIn_{1-x}As_yP_{1-y}$/InP semiconductor laser diode (Oki Electric Industry Co., Ltd.) of wavelength $\lambda = 1410$ nm (0.88 eV) at 83 K. The intensity of the laser diode was 14 mW under the pulsed operation with a repetition time of 0.5 sec. The photoinduced recovery were measured after the full quenching[2] of the hopping conduction due to the illumination using a LED (Hamamatsu photonics L2388) with peak wavelength of 940 nm (1.32 eV). The intensity of the LED was 6 mW under continuous operation. The sample temperature during the illumination was kept at around 84 K.

Figure 1 shows the temperature dependence of the conductance for neutron-irradiated samples annealed at 500 °C, preilluminated with laser-diode light of wavelength $\lambda = 1410$ nm. The hopping conduction was observed at an annealing temperature up to 500 °C. The conductance without preillumination clearly shows hopping conduction, which obeys the relationship[7,8]

$$G_{HP} = G_0 \exp(-b/T^{1/4}) , \quad (1)$$

$$b = A(\alpha R)^{3/2}(W/k)^{1/4} , \quad (2)$$

$$N_{HP} = R^{-3} \times 3/(4\pi) , \quad (3)$$

where A is a constant, 2.95, α^{-1} is the tunneling length $[\alpha = (2m^* E_g/2)^{1/2}/\hbar]$, W is the width of the defect levels, R is the distance between the hopping sites, N_{HP} is the defect concentration associated with the hopping conduction, and the other terms have the usual meaning. W is estimated to be 56 meV from Arrhenius plot of the conductance without preillumination. N_{HP} before photoquenching is estimated to be $\sim 5.8\times10^{17}$ cm^{-3} using the slope (b) of the conductance curve. On the other hand, the preillumination with laser-diode light of wavelength $\lambda = 1410$ nm induces the abrupt change in the conductance at 125 K as observed in our earlier works[1,2] using a LED of wavelength $\lambda = 940$ nm. The reduction of the conductance due to quenching is enhanced with increasing illumination time. This reduction is observed until the preillumination for 120 min. The quenching light used here lies on the lower boundary[6] of the wavelength for the usual photoquenching experiments of *EL*2 defects. Since recent electron-spin resonance experiments[9,10] indicate that the isolated arsenic antisite (As_{Ga}) defect introduced by neutron irradiation does not show the photoquenching phenomenon, the photoquenching behavior observed here originates from both the reduction of the artificial As_{Ga} induced by the neutron irradiation and the appearance of the quenchable component associated with *EL*2 or *EL*2-like defects.[1]

The full quenching[2] of the hopping conduction due to the extreme reduction of the hopping sites is observed in samples annealed at 500 °C, preilluminated with LED light of wavelength $\lambda=940$ nm. The photoinduced recovery is observed after the full quenching (curve *F* in Fig. 1). This recovery reaches a saturated level after the preillumination with laser-diode light of wavelength $\lambda=1410$ nm for 60 min. There is a difference of the saturated level between the photoquenching and photoinduced recovery as shown in Fig. 1. This fact suggests the existence of another quenchable component that is hardly responsive to laser-diode light of wavelength $\lambda=1410$ nm. The neutron-induced quenchable components are likely to exhibit several bonding forms as the quenchable defects well known as the "*EL*2 family."[11] In the recovery process, which starts from the full quenched state, if the photoinduced recovery does not reach its saturated level, the following illumination leads to further recovery; similarly, the quenching process proceeds toward its saturated level. Thus the equilibrium condition for a constant temperature using the same light intensity in each process can be expressed as follows:

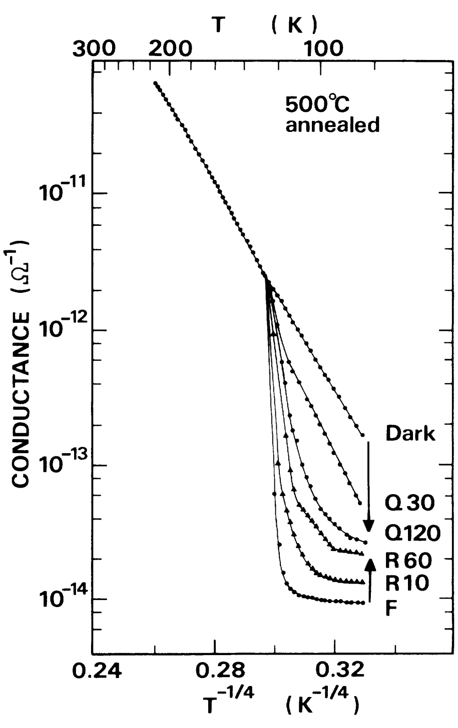

FIG. 1. Temperature dependence of conductance for the samples annealed at 500 °C for 30 min. The curve labeled "dark" presents the conductance without preillumination. Curves *Q*30 (illumination time 30 min) and *Q*120 (120 min) were obtained from samples preilluminated with laser light of $\lambda=1410$ nm. Curves *R*10 (illumination time 10 min) and *R*60 (60 min) were obtained from samples preilluminated with laser light of $\lambda=1410$ nm after the full quenching (curve *F*) due to the illumination with LED of $\lambda=940$ nm for 20 min.

$$N_s\sigma_{OQ}=N_m\sigma_{OR} , \tag{4}$$

where N_s is the concentration of the stable state, N_m is that of the metastable state, σ_{OQ} is the optical quenching cross section, and σ_{OR} is the optical recovery cross section. The ratio of defects in stable and metastable states, N_s/N_m, is estimated from that of the difference in N_{HP} between the dark level and each saturated level. From Eqs. (1)–(3), N_{HP} is proportional to $-(\ln G_{HP})^{-4}$. Since the conductance below 125 K after the preillumination does not show pure hopping conduction, except for the curves, labeled "dark" and *Q*30 in Fig. 1, we correct the conductance (*G*) for the evaluation of N_{HP} as follows:

$$G_{HP}=G-G_b , \tag{5}$$

where G_b is the conductance in the conduction and/or valence bands. The band conductance under the full quenched condition would be written as

$$G_b \geq G_{HP} . \tag{6}$$

To estimate the band conductance, we use the simplest relationship for a rough approximation:

$$G_b \simeq G_{HP} \simeq G_F/2 , \tag{7}$$

where G_F is the conductance of the full quenched state. Substituting the value of N_m/N_s at 85 K into Eq. (4), the ratio of the cross sections for the quenching and recovery processes (σ_{OQ}/σ_{OR}) is estimated to be ~ 1.9 after the conductance correction for the unknown quenchable component. On the other hand, the rate constants K_Q and K_R for the quenching and recovery processes can be evaluated by using the rate equation for a dynamic balance[12] between the quenching and recovery components. The rate constants K_Q and K_R are estimated to be 2.9×10^{-4} and 3.5×10^{-4} sec^{-1}, respectively, using the time constants τ_Q and τ_R evaluated from the illumination-time dependences of the photoquenching factor (ΔQ) and the photoinduced recovery factor (ΔR), as shown in Fig. 2. Although σ_{OQ} is about two times larger than σ_{OR}, the partial photoinduced recovery would occur under 1410-nm (0.88-eV) illumination, as observed in the photoresponse of native *EL*2 defects,[5] since K_R is comparable to K_Q.

Figure 3 shows the conductances recorded in the dark before and after the illumination by light of wavelength $\lambda=1410$ nm for as-irradiated and 250 °C annealed samples. The photoquenching of the hopping conduction is readily observed in samples annealed at around 250 °C, while that for the as-irradiated samples is not affected by

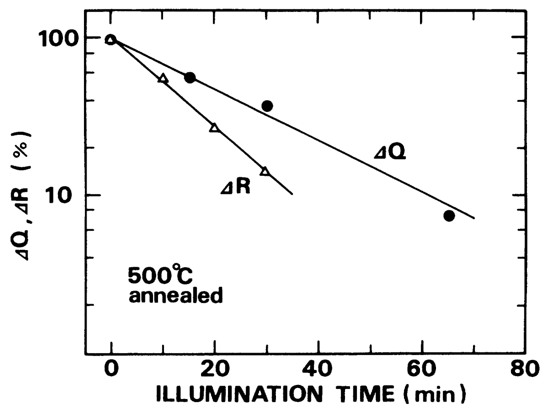

FIG. 2. Transient properties of photoinduced recovery and photoquenching taken as 85 K for the illumination described in Fig. 1. ΔR and ΔQ are defined as $\Delta R=[\gamma_s-\gamma(t)]/(\gamma_s-\gamma_i)$ and $\Delta Q=[\gamma(t)-\gamma_s]/(\gamma_i-\gamma_s)$, respectively, where $\gamma(t)\equiv-[\ln G_{HP}(t)]^{-4}$, and γ_s and γ_i are the values for the saturation and initial levels, respectively. The time constants τ_Q and τ_R are estimated to be 26 and 15 min, respectively.

preillumination as described in our previous works[1,2] using a LED of wavelength $\lambda=940$ nm. The full quenching of the conductance for the 250 °C-annealed sample was not achieved even if the samples were illuminated by the LED for 80 min. This indicates that a major origin of the hopping conduction is an unquenchable component, such as the artificial As_{Ga} defects, since N_{HP} before and after the illumination of the quenching light are 6.2×10^{17} and 5.1×10^{17} cm^{-3}, respectively. The unquenchable component corresponds to 84% in the net hopping site. Therefore, the photoexcitation would occur mainly in the unquenchable component without exhibiting the photoinduced recovery. The appearance of the quenchable component due to the annealing at 250 °C supports our previous work[1] that the neutron-induced $EL2$ defects are likely to be formed by the interaction between the isolated As_{Ga} and a mobile defect[13] such as an arsenic interstitial (As_i) (Ref. 14) and the divacancies[15,16] consisting of a Ga vacancy (V_{Ga}) and an As vacancy (V_{As}). We cannot confirm whether As_i is more mobile than the divacancy at lower temperature at present.

In conclusion, we observed the photoinduced recovery

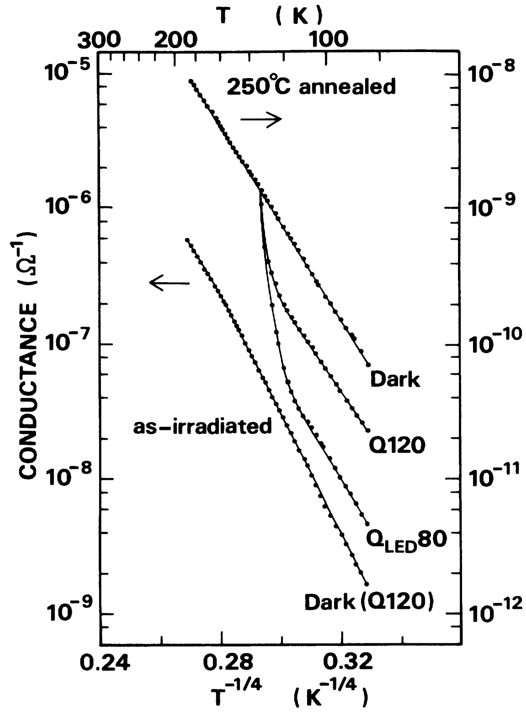

FIG. 3. Temperature dependence of conductances for as-irradiation and annealing at 250 °C for 30 min. The curve labeled "dark" presents the conductance without preillumination. Curves $Q120$ (illumination time 120 min) were obtained from samples preilluminated with laser light of $\lambda=1410$ nm. Curve Q_{LED} 80 was obtained from the sample preilluminated with LED of $\lambda=940$ nm for 80 min.

of the tunneling-assisted hopping conduction, which has been fully photoquenched previously, in neutron-irradiated GaAs annealed at 500 °C. The results presented here support the interpretation that neutron-induced $EL2$-like defects are likely to be identified as native $EL2$ defects having several quenchable components.

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