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Recovery of quenched hopping conduction in GaAs layers grown by molecular-beam epitaxy at 200 °C

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The dark current at 82 K, in GaAs layers grown by molecular-beam epitaxy at 200 °C and annealed at 550 °C, is reduced by a factor 350 after 5 min of IR ($h\nu \lesssim 1.12$ eV) light illumination. As temperature is swept upward at 0.2 K/s, the current recovers rapidly near 130 K. A numerical analysis of the current recovery, based on hopping conduction, gives an excellent fit to the data for a thermal recovery rate $r = 3\times10^8 \exp(-0.26/kT)$, very close to the rate observed for $EL2$ (As_{Ga}). This proves that the conduction below 300 K in this material is due to hopping between As_{Ga}-related centers in their ground states. Variable-range hopping $[\exp-(T_0/T)^{1/4}]$ gives a slightly better fit to the data than nearest-neighbor hopping $[\exp(-\epsilon_3/kT)]$ in the range $T = 82-160$ K, but the fitted recovery rate is not strongly affected no matter which mechanism is assumed.

INTRODUCTION

GaAs layers grown by molecular-beam epitaxy (MBE) at 200 °C, far below the normal growth temperature of 580–600 °C, have been widely studied in the past few years because of many device applications.[1] They also represent a unique system for defect studies because of the presence of $\sim10^{20}$ cm^{-3} arsenic antisites (As_{Ga}) and $10^{18}-10^{19}$ cm^{-3} acceptor defects, probably related to V_{Ga}.[2] There is good evidence that the major contribution to the 300-K conductivity results from hopping among the As_{Ga} centers,[3] although a definitive proof of this assertion has been lacking. Recently we have discovered that the dark current measured below 120 K can be quenched by infrared (IR) light, thus giving more credence to the hopping mechanism since it is well known that As_{Ga} centers can be transformed to a metastable state As_{Ga}^* by IR light.[4] In this paper we show that the recovery of the current, as temperature is swept upward, is exactly what is expected for the $As_{Ga}^* \rightarrow As_{Ga}$ reaction, thus proving that the hopping is between As_{Ga} centers, and also proving that the metastable As_{Ga}^* does not participate in the hopping. Kuriyama, Yokayama, and Taniguchi[5] also very recently observed that hopping conduction due to As_{Ga} centers can be quenched, but in a different system, i.e., neutron-irradiated GaAs. However, they did not study the recovery kinetics in detail.

EXPERIMENT

The sample was grown in a modified Varian 360 system to a thickness of 2 μm on a 650-μm-thick semi-insulating (SI) GaAs wafer. The substrate was not In bonded to the sample holder, so that it was necessary to determine the sample temperature (200 °C) from a thermocouple sitting in the vacuum very close to the substrate. The beam-equivalent pressure during growth was $As_4/Ga = 20$, and the layer grew in a 1×1 surface-reconstruction pattern as observed by reflection high-energy electron diffraction (RHEED). After growth, a 6 mm$\times$6 mm sample was cut from the wafer and then annealed at 550 °C for 10 min in a furnace purged with flowing N_2. To inhibit As loss, another GaAs wafer was placed on top of the layer of interest during the anneal.

Because a GaAs layer that is grown by MBE at 200 °C and annealed at 550 °C has a high resistivity ($>10^5$ Ω cm at 300 K), it is necessary to remove the substrate in order to insure accurate conductivity measurements and inhibit other substrate interferences. The present layer was epoxied onto an 8 mm $\times$10 mm piece of glass (microscope slide), and the substrate was removed by a technique described elsewhere.[6] Indium contacts were soldered onto the four corners of the layer, but not annealed. The sample was then placed in the cryostat of a modified Bio-Rad DL4600 spectrometer and the current between two of the diagonal contacts was measured under 20-V bias, while the temperature was swept at 0.2 K/s from 82–180 K. The currents were measured in the dark, both with and without a prior 5-min illumination at 82 K from an 8-W tungsten lamp filtered by a Si wafer (so that $h\nu \lesssim 1.12$ eV). This initial illumination caused a decrease in the current at 82 K by a factor of 350, i.e., it quenched the current. However, note that this quenching pertains to the *dark* current, not the photocurrent. (The latter is well known to be quenchable in many cases.)

THEORY

Hopping conduction is usually discussed in terms of two different mechanisms: (1) nearest-neighbor (NN) hopping and (2) variable-range (VR) hopping.[7,8] For low compensation, the NN hopping may be explained rough-

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ly in the following way: The donor which is closest to a given acceptor will have a higher energy for occupation than the other donors because of Coulomb repulsion from the negatively charged acceptor. Thus, this donor will be empty, and a hop to it will require an energy $\epsilon_3 \sim e^2/4\pi\kappa R$, where $R \simeq (3/4\pi N_D)^{1/3}$ is the average distance between donors and κ is the dielectric constant. Such a hop will be the rate-limiting step in the whole transport process because hopping between the other donors will not require nearly as much thermal energy. Another important factor is wave-function overlap, which will introduce an approximate factor $\exp(-2R/a)$ for a wave function which has a radial variation $\exp(-r/a)$, where $a = \hbar/(2m^*E_D)^{1/2}$ in the hydrogenic approximation. A somewhat more detailed analysis[8] gives

$$\sigma_{NN} = C_{NN} e^{-\gamma' R/a} e^{-K_3 e^2 (N_D^0)^{1/3}/4\pi\kappa kT}$$
$$= C_{NN} e^{-\gamma (N_D^0)^{-1/3} a^{-1}} e^{-B_{NN}(N_D^0)^{1/3} T^{-1}} , \quad (1)$$

where $\gamma \simeq 1.8$ and $K_3 \simeq 0.99$, and N_D^0 is the concentration of donors taking part in the hopping process. At low temperature, ϵ_3/kT becomes large, and nearest-neighbor hopping becomes more improbable. Then variable-range hopping, which involves greater distances but smaller energy changes, takes over and often can be described by the form

$$\sigma_{VR} = C_{VR} e^{-(T_0/T)^{1/4}}$$
$$= C_{VR} e^{-A_{VR}(N_D^0)^{-1/4} T^{-1/4}} , \quad (2)$$

where, in one analysis,[5] $T_0 \simeq 76(w/k)(\alpha R)^3$. Here w denotes the width of the defect band, $\alpha \simeq (m^* E_g)^{1/2}/\hbar$ is a tunneling length, and k is Boltzmann's constant.

After illuminating the sample at 82 K with IR light, a large fraction of the As_{Ga} centers become metastable, i.e., $N_D^0 \rightarrow N_D^*$, where $N_D^0 + N_D^* = N_D$. Then, during the temperature sweep, the reverse transformation takes place, described by

$$\frac{dN_D^0}{dT} = \frac{1}{\beta}\frac{dN_D^0}{dt} = \frac{\nu}{\beta} N_D^* = \frac{\nu_0}{\beta} e^{-E_b/kT} N_D^*$$
$$= \frac{\nu_0}{\beta} e^{-E_b/kT} (N_D - N_D^0) , \quad (3)$$

where E_b is the thermal recovery barrier, ν_0 is the preexponential factor, and β is the heating rate. The solution of Eq. (3) is

$$[N_D - N_D^0(T)] = [N_D - N_D^0(T_i)]$$
$$\times \exp\left\{ -\int_{T_i}^{T} \frac{\nu_0}{\beta} e^{-E_b/kT} dT \right\} , \quad (4)$$

where T_i is the initial temperature, 82 K in our case. Equation (4) must be solved simultaneously with either Eq. (1) or Eq. (2) to fit the data.

RESULTS AND DISCUSSION

The current I versus temperature T data are presented as a function of 82-K illumination time in Fig. 1. These

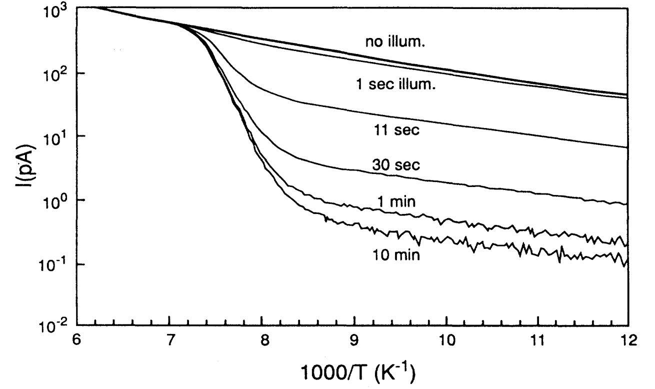

FIG. 1. Current vs inverse temperature for various IR illumination times at 82 K.

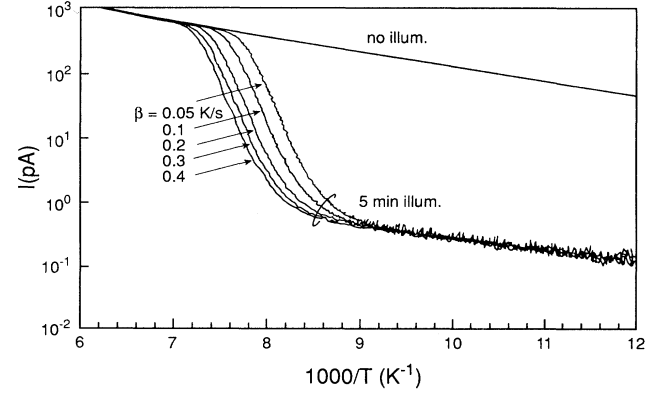

FIG. 2. Current vs inverse temperature for various heating rates after IR illumination of 5 min at 82 K.

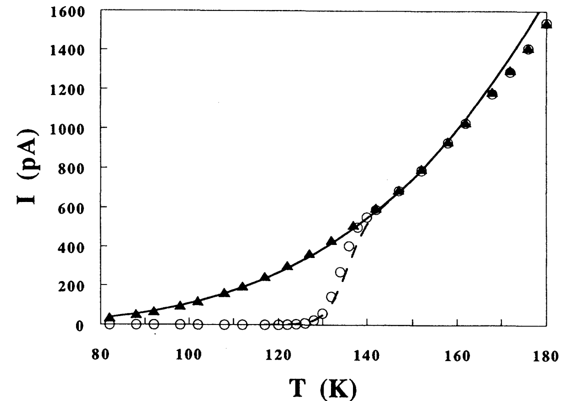

FIG. 3. Current vs temperature after a 5-min IR illumination at 82 K (dashed line) and no illumination (solid line). The heating rate was 0.3 K/s.

TABLE I. Fitting parameters for I-T data. The value for N_D was fixed.

Assumed hopping type	N_D	N_D^0 (after illumination)	E_b	ν_0
Nearest neighbor	1.44×10^{19} cm^{-3}	1.4×10^{18} cm^{-3}	0.26 eV	1.4×10^{8} s^{-1}
Variable range	1.44×10^{19} cm^{-3}	4.9×10^{18} cm^{-3}	0.26 eV	3.0×10^{8} s^{-1}

data should be contrasted with those generated in a standard thermally stimulated current (TSC) experiment which is conducted in exactly the same way. That is, in a TSC experiment the sample is briefly illuminated at low temperature to fill the traps, and then temperature is swept upward to empty the traps individually and thus produce peaks in the I-T spectrum. (Indeed, the present study began as a TSC experiment.) However, the TS current is always *higher* than the dark current, whereas the current observed in Fig. 1 is lower and does not produce a peak. Clearly, the illumination at 82 K is simply reducing the dark current in this case. As shown in Fig. 2, an increase in heating rate β moves the transition region to higher temperatures, as would be expected in a thermally activated process.

The I-T data after an 82-K illumination time of 5 min are shown in Fig. 3, along with the data after no 82-K illumination (no quenching). Here, $\beta=0.2$ K/s and a linear plot is used to illustrate the high degree of current quenching. The solid line is derived from a least-squares fit of the nonquenched data, using Eq. (2) (variable-range hopping), while the dashed line is the fit of the quenched data, using Eqs. (2) and (4). The best-fit parameters are given in Table I. The data were also fitted with the nearest-neighbor formula [Eq. (1)], and the fit to the unquenched curve was somewhat better for $T > 160$ K, but somewhat worse below that. This is not surprising, because the activated hopping will begin to dominate at higher temperatures. However, both fits are basically good and, as seen in Table I, the deduced parameters are quite similar. The variable-range-hopping parameters are perhaps slightly more accurate since Eq. (2) fits the unquenched curve better than Eq. (1) in the region near $T=130$ K, where the recovery takes place. A fit of data for $\beta=0.05$ K/s instead of 0.2 K/s gives nearly the same parameters.

The stated donor concentration $N_D \simeq 1.44\times10^{19}$ cm^{-3} was calculated independently from a fit of Hall-effect data from 300–500 K.[6] In this temperature range, band conduction becomes strong, so that an accurate value of N_D can be deduced from the Hall effect. Obviously, it fits the present data well also. Thus, we feel confident that our values of $E_b=0.26$ eV and $\nu_0=3.0\times10^{8}$ s^{-1} are also credible and representative of the deep centers responsible for the hopping conduction. Indeed, Mohapatra and Kumar[9] give $E_b=0.26$ eV and $\nu_0=2.5\times10^{8}$ s^{-1} for $EL2$, surprisingly close to our values. Most other measurements of these quantities are also within this range.[9,10] Thus, we have proven beyond a reasonable degree of uncertainty that the hopping is between $EL2$- or As_{Ga}-like defects and that the metastable defect does not take part in the hopping process. This study also indirectly shows that the large As precipitates,[11] which exist in material grown at 200 °C and annealed at 550 or 600 °C, have no influence on the hopping mechanism.

As a further point, we may note that samples annealed at lower temperatures $T_A \lesssim 350$ °C, or not annealed at all, do not show quenching of the hopping conduction, but it is also known that they do not show quenching of the photocurrent[4] or absorption.[12] The question remains as to whether a different (nonquenchable) type of As_{Ga} center exists in the as-grown samples, or whether the nonquenchability is simply due to a different environment, perhaps involving the strain which is present in samples annealed below 350 °C.[13] This question must await further study.

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