Giant resistance changes in (Al,Ga)As contact layers of GaAs/AlAs superlattices due to deep donors

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For transport studies on semiconductor superlattices under optical excitation, samples with highly Si-doped (Al,Ga)As contact layers are used due to their optical transparency. These samples exhibit a giant increase of the resistance at temperatures below 200 K. Likewise, the current plateau in the $I-V$ characteristics, which contains the region of current self-oscillations, is shifted towards higher voltages. However, the oscillation frequencies remain unchanged. The current decreases during cooling by as much as seven orders of magnitude. The giant resistance can be compensated for at low temperatures by applying a high dc voltage or by weak illumination. The optically induced current transients are shown to be controlled by thermally activated processes. On the basis of the activation energies derived, it is suggested that the dramatic resistance changes are mainly due to deep donors, i.e., well-known DX centers, in the (Al,Ga)As contact layers. The effects are negligible, if GaAs contact layers are used. Possible DX centers at the AlAs/GaAs interfaces inside the superlattice structure can be therefore neglected.
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I. INTRODUCTION

Semiconductor superlattices (SLs) are interesting structures for the investigation of miniband transport,[1,2] Bloch oscillations,[3,4] domain formation,[5,6] self-generated current oscillations,[7,8] and chaos.[9] Transport studies in SLs are not only performed by electrical injection, but also by optical generation of carriers inside the SL structure itself. SLs are usually subjected to an electric field perpendicular to the layers. In order to achieve, at the same time, optical access for photoexcitation or detection of an optical signal (e.g., photoluminescence spectroscopy), either very thin contact layers of the well material or window layers with a band gap larger than the photon energy for excitation have to be used. For optical investigations of GaAs/AlAs SLs, highly doped $Al_{0.5}Ga_{0.5}As$ window layers are commonly utilized as p-type or n-type contact layers.[10,11]

In this article, we show that the current–voltage ($I-V$) characteristics of weakly coupled SLs embedded in n^+-n-n^+ structures change remarkably as a function of the temperature, illumination, and electric field. The current decreases at temperatures below 200 K much more than estimated from thermally activated transport through the SLs. The current plateau in the $I-V$ characteristics, which contains the region of current self-oscillations, is shifted towards higher voltages. However, the oscillation frequencies remain unchanged. By applying high electric fields or optical excitation, the current can be completely restored. After such activation, the current persists for hours at temperatures below 50 K. The effects observed are very weak in samples with GaAs contact layers. We conclude that the low-temperature behavior originates from the deep donors (DX centers) in the Si-doped (Al,Ga)As contact layers.

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II. EXPERIMENTAL DETAILS

Four different structures are investigated: two with and two without optical window layers consisting of (Al,Ga)As. All samples are grown by molecular beam epitaxy on n^+ substrates with 40 periods in the SL region. The SLs of samples A and D consist of 9.0 nm GaAs wells and 1.5 nm AlAs barriers. Sample B has 15 nm GaAs wells and 0.85 nm AlAs barriers, while sample C contains 9.0 nm GaAs wells and 4.0 nm AlAs barriers. The center 5.0 nm (9.0 nm for sample B) of each well is Si doped with a donor density N_D of $5\times10^{16}\,\mathrm{cm}^{-3}$. For samples A and B, the SL is sandwiched between two graded $Al_xGa_{1-x}As$ layers ($x=0\rightarrow0.5$, $N_D=0\rightarrow2\times10^{18}\,\mathrm{cm}^{-3}$, 90 nm thick), followed by $Al_{0.5}Ga_{0.5}As$ layers ($N_D=2\times10^{18}\,\mathrm{cm}^{-3}$, 300 nm thick) and an additional graded layer of $Al_xGa_{1-x}As$ ($x=0.5\rightarrow0$, $N_D=2\times10^{18}\,\mathrm{cm}^{-3}$, 170 nm thick) on the substrate side. Sample C has the same contact region on the substrate side, but a thin, highly doped GaAs top contact layer of 55 nm thickness. For sample D, GaAs contact layers are used on both sides. A sketch of the Al content x_{Al} of the contact layers is shown in Fig. 1 for the different samples.

The samples are supplied with ohmic contacts and etched into mesas with diameters of between 16 and 120 μm. Sample A is encapsulated in a chip holder together with a red light-emitting diode (LED) with a wavelength of 634 nm and mounted into a He flow cryostat. Samples B, C, and D are mounted onto sapphire holders in the cryostat using the same type of LED near the sample. The LEDs have a minimal operating temperature of 70 K. The $I-V$ characteristics and current transients $I(t)$ are recorded using a source-measure unit (Keithley SMU 236).

III. RESULTS

Figure 2 shows $I-V$ characteristics of sample A recorded in the dark at the different temperatures indicated.

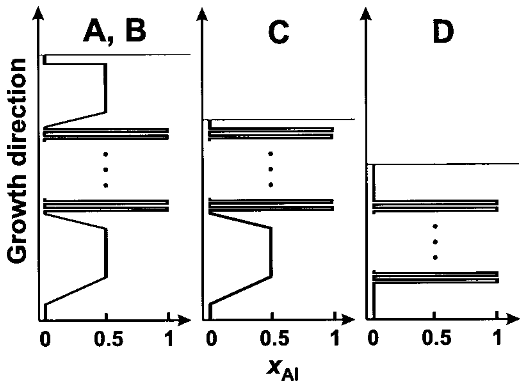

FIG. 1. Sketch of the Al mole fraction x_{Al} in structures A, B, C, and D.

Before the first measurement, 10 V was applied for several seconds at 6 K. Then, we heated the sample to 50 K and recorded the $I-V$ trace (labeled 50 K in Fig. 2). At each temperature, voltage sweeps were performed from 0 to $+8$ V. The characteristics for the other polarity are almost identical. All curves in Fig. 2 reveal a current plateau, which is typical of vertical transport through weakly coupled SLs in this carrier density regime.[12] In the temperature range of 100–150 K, we observe unusual transport properties. The current plateau in the $I-V$ characteristics, which contains the region of current self-oscillations, is shifted towards much higher voltages. However, the oscillation frequencies remain unchanged (not shown). At voltages below 3 V, the current remains very small, in contrast to the behavior below and above the temperature range given. The very low current level can be activated by high voltages or illumination.

A. Activation by high voltages

When sample A is cooled down in the dark, the current in the low-voltage region decreases by as much as seven orders of magnitude. This low conductivity can be strongly enhanced by applying a high voltage for a certain period of time (e.g., 10 V for 30 s). The results of a detailed investigation of this type of activation are shown in Fig. 3, where the current is plotted on a semilogarithmic scale. For the voltage sweeps performed at 6 K from 0–2,3,...,6 V, the $I-V$ characteristics remain the same as for a sweep from 0 to 7 V (curve 1 in Fig. 3). However, when the sweep is extended to 8 V, the current starts to increase over the whole voltage range as shown by curve 2 in Fig. 3. Sweeping a second time up to 8 V results in a further increase of the current (curve 3 in Fig. 3). The final current level is reached when the voltage is kept at 8 V for 5 min (curve 4 in Fig. 3). Note that at 1.4 V the current can be activated by seven orders of magnitude (cf. the vertical line in Fig. 3), i.e., the high-temperature current level can be completely restored by the application of a high electric field. Furthermore, the current activated by high voltages persists for several hours.

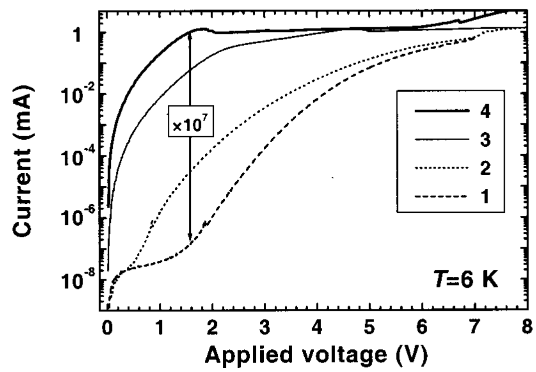

FIG. 3. $I-V$ characteristics of sample A at 6 K on a semilogarithmic scale for different voltage sweeps. Curve 1 was recorded by sweeping from 0 to 7 V, while sweeps from 0 to voltages smaller than 7 V follow curve 1. Curve 2 corresponds to the first sweep up to 8 V, while curve 3 shows one of four additional sweeps from 0 to 8 V, which are basically identical. Curve 4 originates from a sweep from 0 to 8 V after applying a voltage of 8 V for 5 min. The maximum increase of the low-temperature current by high electric fields is marked by the vertical line.

B. Activation by illumination

The current level at low temperatures can be also recovered by illumination with red light. The results of optical activation at 70 K are displayed in Fig. 4. Before illumination, the $I-V$ characteristics were activated in the dark by high voltages (set A). The $I-V$ characteristics labeled B, C, and D in Fig. 4 were obtained after having driven the LED successively for periods of 1, 4, and 14 min, respectively. Additional illumination did not change the $I-V$ characteris-

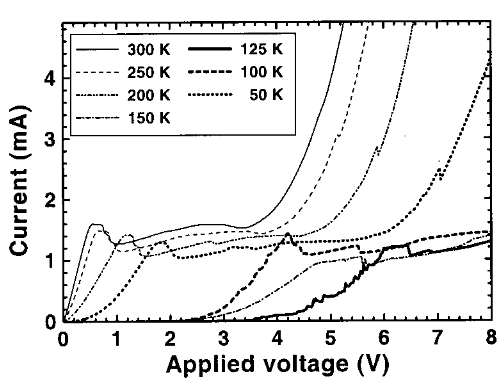

FIG. 2. $I-V$ characteristics of sample A recorded for the different temperatures indicated. Before the first measurement, 10 V was applied for a few seconds. All sweeps were performed from 0 to 8 V.

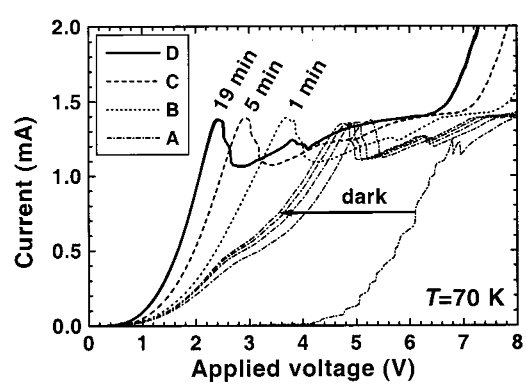

FIG. 4. $I-V$ characteristics of sample A for voltage sweeps from 0 to 8 V for different illumination conditions at 70 K. The set of curves labeled A was recorded successively from right to left without illumination. Curves B and C correspond to voltage sweeps after cumulative illumination for 1 and 5 min, respectively. Curve D was recorded after 19 min of illumination.

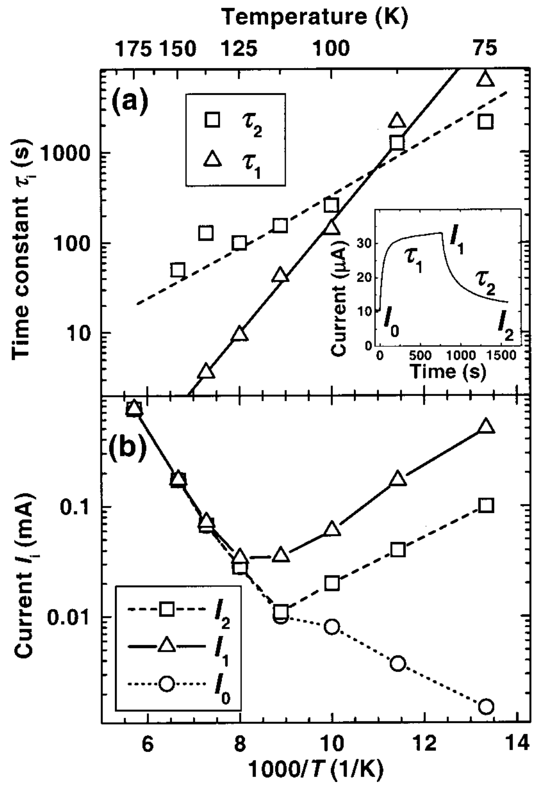

FIG. 5. (a) Rise τ_1 and decay times τ_2 as well as (b) saturation currents I_0, I_1, and I_2 vs inverse temperature T for sample B at a voltage of 2 V and constant LED current. The inset shows a typical current transient.

tic. Note that the maximum and minimum of the current at the beginning of the plateau as well as the voltage range of the plateau do not vary with the illumination conditions.

In the following, current transients in the optical activation regime are presented. A typical current transient of sample B is shown in the inset of Fig. 5(a). When the LED is switched on, the current increases from I_0 and saturates at I_1. After switching off the LED, the current decays and saturates at I_2. The initial rise and decay are fast and are followed by a slow exponential transient.

The time traces can be reproduced very well by the stretched exponential function,[13]

$$I(t)=I_i+\Delta I_i \exp\left[-\left(\frac{t}{\tau_i}\right)^{\beta}\right], \quad (1)$$

where i refers to 1 or 2, $\Delta I_1=I_0-I_1$, and $\Delta I_2=I_1-I_2$. From fits of the experimental current transients to Eq. (1), the exponent β is found to be about 0.7. The derived rise and decay times τ_1 and τ_2 as well as the saturation currents I_0, I_1, and I_2 are plotted in Figs. 5(a) and 5(b), respectively, as a function of inverse temperature T. The results for sample A are found to be similar. It should be noted that the rise time τ_1 at a fixed temperature is inversely proportional to the current of the LED, i.e., the illumination intensity. However, the distinct T dependence of τ_1 is not affected by the illumination intensity.

The Arrhenius plots for τ_1 and τ_2 in Fig. 5(a) exhibit a linear increase with inverse temperature over the whole temperature range according to

$$\tau=\tau_\infty \exp\left(\frac{E}{k_B T}\right), \quad (2)$$

where τ_∞ is the time constant at high temperatures, E the corresponding thermal activation energy, and k_B the Boltzmann constant. The values increase from a few seconds at 175 K to about 1 h at 75 K. From the slopes in Fig. 5(a), we obtain for the rise and decay processes thermal activation energies of about 110 and 55 meV, respectively.

Distinct current transients are observed only below 125 K [see Fig. 5(b)], where the saturation currents I_1 and I_2 increase with decreasing temperature. The temperature dependence of I_0 reflects the thermally activated current regime in the dark.

C. Samples with GaAs contact layers

For sample C with a thin GaAs top and an (Al,Ga)As bottom contact layer, the above effects are less pronounced. Its conductivity at low temperatures is reduced by only three orders of magnitude in contrast to samples A and B. Electrical activation is achieved with a voltage of 4 V, about half the value needed to activate sample A. The current can also be completely recovered as discussed for samples A and B. Because the mesa of sample C is only partially covered by the upper metallic contact (a much larger mesa than for samples A and B), the light reaches the (Al,Ga)As layer directly from the top. The illumination intensity for sample C is therefore higher in comparison with that of samples A and B. Thus, the rise times τ_1 are considerably shorter under comparable illumination conditions (cf. Sec. III B), but the related Arrhenius plot results in the same thermal activation energy of about 110 meV. The decay times τ_2 for sample C are similar to those observed for samples A and B at corresponding temperatures.

Sample D with two GaAs contact layers shows almost no variation of the current with temperature. The response to illumination at 125 K is very weak. When the LED is switched on, the current rises only by about 1%. The decay time is found to be 25 s, which is very similar to the decay times of samples A and B at this temperature.

IV. DISCUSSION

The distinct behavior of SL structures embedded in n^+-n-n^+ diodes below 200 K originates mainly from the highly Si-doped (Al,Ga)As contact layers. It is known that the electrical properties of (Al,Ga)As material are determined at low temperatures by the so-called DX centers.[14,15] We therefore assume that these deep electron traps are responsible for the unusual characteristics. DX centers are related to Si atoms in (Al,Ga)As. It is widely accepted that these electron traps are associated with isolated donor atoms. The related deep levels can be occupied by two electrons displacing the donor atoms away from the lattice site of the shallow level.[16,17]

Our results can be explained completely by the presence of DX centers in the contact layers. The conductivity of (Al,Ga)As layers can be strongly reduced at temperatures below 150 K due to efficient electron capture by DX

centers.[15] This feature is confirmed by the giant rise of the resistance of samples A and B in the dark (see Fig. 3). The recovery of the low-temperature current using high voltages (Fig. 3) is possible, because captured electrons can be released from *DX* levels by impact ionization.[18] The avalanche process related to carrier release that is expected is partially suppressed by the resistance of the SL region.

The optically induced current transients at low temperatures (see Fig. 5) are due to emission and capture processes of electrons at *DX* centers. In particular, the transients are linked to resistance changes in the contact layers. By switching the LED on, the resistance of the $Al_{0.5}Ga_{0.5}As$ layers is suddenly decreased due to the electrons, which are released from the *DX* centers. The time constant τ_1 of the current transient is therefore directly related to the value of this resistance. Hence, the temperature dependence of τ_1 is ruled by the true level energy of the *DX* centers. We can therefore derive from Fig. 5(a) a level energy of about 110 meV. This activation energy is in satisfactory agreement with values between 110 and 150 meV for the deep donor level, which have been obtained from transport studies on Si-doped $Al_{0.5}Ga_{0.5}As$ layers.[19–21] For larger illumination intensities, the time constant τ_1 is smaller due to the lower resistance of the contact layers, in agreement with the experimental findings in Sec. III B. However, determination of the level energy is not affected by the light intensity. Although the temperature and intensity dependence of the emission processes can be understood well in the model presented, the absolute value of the rise time appears to be rather large.

Thermally activated capture of electrons is a peculiar property of *DX* centers.[14,15,22,23] For the time constant τ_2, we find a thermal activation energy of 55 meV, which is not consistent with the values of around 250 meV commonly measured by capacitance spectroscopy.[23] However, with an increase of applied electric field, the activation energy for capture processes in $Al_{0.5}Ga_{0.5}As$ is reduced.[24] By switching the light source off in our transport experiments, the resistance of the contact layers increases continuously due to the capture of electrons by *DX* centers. The decay time of the current in Fig. 5 therefore increases with an increase in time as also demonstrated by the stretched exponential used for fitting the transients. The value of the apparent thermal activation energy for the capture process depends therefore largely on the time interval that is chosen for evaluation of the current transient.

The persistent photoconductivity observed under conditions of optical activation, i.e., the difference between I_2 and I_0 shown in Fig. 5(b), is linked with the capture barrier of *DX* centers.[14,15] It should be noted that the very weak optical activation found for samples with GaAs contact layers is probably due to residual *DX* centers at the GaAs/AlAs heterointerfaces of the SL region.

Since the unusual characteristics of SL structures embedded in n^+-n-n^+ diodes originate from the reduced conductivity of the highly doped (Al,Ga)As contact layers at lower temperatures, the electric-field distribution in the current plateau regime is not directly influenced inside the SL region. The general shape of the $I-V$ characteristics at low temperatures is therefore maintained in the dark (Fig. 2) as well as after electrical (cf. Fig. 3) and optical activation (Fig. 4). Thus the frequency range of the current oscillation in the SL is not affected.

For electrical measurements on heterostructures with Si-doped (Al,Ga)As contact layers at low temperatures, it is necessary to keep the density of free electrons on a high and constant level for a long time in order to reduce *DX*-related effects. After electrical or optical activation, the corresponding decay times are usually long enough so that the $I-V$ characteristics are stable.

V. SUMMARY AND CONCLUSIONS

At low temperatures, Si-doped (Al,Ga)As contact layers deteriorate the electrical properties of weakly coupled, doped GaAs/AlAs superlattices embedded in n^+-n-n^+ structures. The $I-V$ characteristics can be restored by high electric fields or illumination with red light. Current transients under optical activation result in activation energies that are typical of *DX* centers. The electrical properties remain basically unchanged when GaAs contact layers are used instead. Therefore, we conclude that *DX* centers in the (Al,Ga)As contact layers are responsible for the strong suppression of the current below 200 K.

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