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Transition between static and dynamic electric-field domain formation in weakly coupled GaAs/AlAs superlattices

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The transition between static and dynamic electric-field domain formation has been investigated in undoped, photoexcited GaAs/AlAs superlattices by varying the carrier density and temperature. The frequency spectra of the photocurrent oscillations exhibit as a function of bias voltage regions without any current oscillations. With decreasing carrier density or increasing temperature, these voltage regions become narrower. These observations indicate that with increasing carrier density the domain formation changes from dynamic to static. However, thermal activation appears to enhance the formation of dynamic domains. [S0163-1829(98)52036-X]

The formation of electric-field domains in weakly coupled semiconductor superlattices (SL's) is known to reveal a static and dynamic regime depending on the carrier density present in the SL. For very large carrier densities, the current-voltage characteristics of these SL's exhibit discontinuities and a series of current branches as a consequence of *static* electric-field domain formation.[1,2] A charge monopole is formed at the domain boundary, which separates the low- and high-field domains. However, if the carrier density is reduced below a certain value, self-sustained current oscillations appear originating from *dynamic* electric-field domain formation,[3] which have been experimentally observed within the last few years.[4–7] These oscillations are caused by the periodic motion of the domain boundary, when the carrier density is not sufficiently large to form static domains. Furthermore, in doped SL's with an external driving voltage, the appearance of chaos has been predicted using numerical simulations.[8] The observation of driven chaos in SL's under domain formation was subsequently reported.[9]

The carrier density dependence of domain formation cannot be easily measured in doped SL's. However, undoped, photoexcited SL's allow us to perform a detailed experimental investigation of the carrier density dependence of the transition between dynamic and static domain formation. Furthermore, most of the previous experiments have been performed at low temperatures, while a few reports have appeared focusing on the temperature dependence of the oscillatory behavior up to room temperature.[4,5] The influence of thermal activation on the transition between the dynamic and static regimes has not been the focus of any previous temperature dependent measurements.

In this paper, we report on the transition region between static and dynamic domain formation in an undoped, photoexcited SL. With increasing carrier density, a transition from a more dynamic to a more static domain formation can be observed. However, for a fixed carrier density, the effect is reversed with increasing temperature.

The investigated sample consists of a nominally undoped, 40-period SL with 9.0 nm GaAs wells and 4.0 nm AlAs barriers grown by molecular beam epitaxy on a (001)-oriented n^+-GaAs substrate. The intrinsic region containing the SL is sandwiched between two heavily n- and p-doped $Al_{0.5}Ga_{0.5}As$ layers. A heavily Be-doped p^+-GaAs layer is deposited on top of the sample to form a p-i-n diode. The sample is structured into mesas of $50\times 50\ \mu m^2$. A cw He-Ne laser beam is focused by a $10\times$ objective lens onto the p-cap layer (beam diameter about 20 μm) to photoexcited carriers in the intrinsic region. The two-dimensional carrier density in the SL region is estimated to be of the order of 10^{11} cm^{-2} per 1 mW HeNe laser excitation. The sample is mounted in a closed-cycle cryostat. Ohmic contacts are used to apply an electric field to the p-i-n diode. The time-averaged photocurrent-voltage (PC-V) characteristics are recorded with an HP 4145B semiconductor parameter analyzer. The frequency spectra of the PC oscillations are detected with an HP 8566B spectrum analyzer.

The frequency spectra of PC oscillations and the corresponding time-averaged PC-V characteristic are shown in Figs. 1(a) and 1(b), respectively, for a laser intensity of 2 mW recorded at 20 K. The spectra are presented on a gray scale, where darker areas correspond to larger amplitudes of the PC oscillations. We will focus on the second plateau region of the PC-V characteristic, which is formed between 5 and 8 V, since self-sustained PC oscillations are only observed in this voltage region. This second plateau is known to originate from the coexistence of a low-field domain caused by $\Gamma_1 \rightarrow \Gamma_2$ resonant tunneling and a high-field domain connected to $\Gamma_1 \rightarrow X_1$ resonant transfer.[4,7] In undoped, photoexcited SL's, Γ-X transfer is necessary for the observation of undamped PC oscillations, because only the indirect nature of the energy gap in the AlAs barriers due to X states leads to a sufficiently large prolongation of the lifetime of photogenerated carriers.[7] As shown in Fig. 1(a), un-

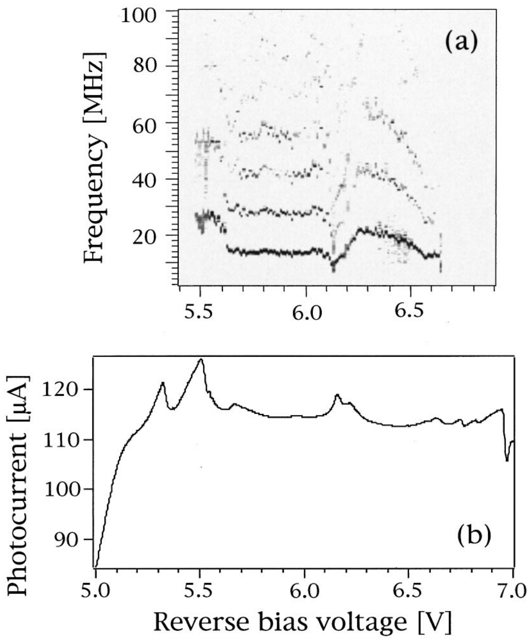

FIG. 1. (a) Frequency spectra of self-sustained photocurrent oscillations and (b) the corresponding time-averaged PC-voltage characteristic for a laser intensity of 2 mW recorded at 20 K and plotted on the same voltage scale. The darker areas in (a) correspond to larger amplitudes.

damped PC oscillations are detected continuously in the voltage range from 5.48 to 6.64 V for a laser intensity of 2 mW at 20 K. In the oscillation regime, the time-averaged PC-V curve exhibits a pronounced maximum at about 6.15 V, where the voltage dependence of the corresponding fundamental frequency shows a local minimum [cf. Fig. 1(a)].

Current self-oscillations in weakly coupled SL's appear, if the carrier density is not sufficiently large to form static domains. Thus, the oscillation behavior shown in Fig. 1(a) can drastically change, when the carrier density is increased. For an excitation intensity of more than 3 mW, the SL system begins already to reveal some voltage regions between 5.48 and 6.64 V, where no PC oscillations are detected. Figures 2(a) and 2(b) display the frequency spectra and time-averaged PC-V characteristic, respectively, for a laser intensity of 3.5 mW recorded again at 20 K. The full voltage region, where PC oscillations are observed, is reduced to 5.77 to 6.52 V. Furthermore, inside this voltage region, two windows from 5.90 to 6.01 V and 6.07 to 6.26 V appear, where the SL does not exhibit any oscillations. Moreover, the corresponding PC-V characteristic in these static windows exhibits more fine structure than the PC characteristic in Fig. 1(a), indicating that the electric-field distribution is changed from a dynamic to a static one. Most of the frequency spectra in the oscillatory windows are broadened as a consequence of undriven chaos as reported by Zhang *et al.*[10] By increasing the carrier density even further, the static windows become wider at the expense of the oscillatory windows. When the laser intensity is larger than 8 mW, the electric-field distribution becomes static over the whole voltage range, and PC oscillations are not detected anymore. These results show that for laser intensities between 3 and 8 mW the SL exhibits a transition between dynamic and static electric-field domain formation and vice versa by simply changing the bias voltage.

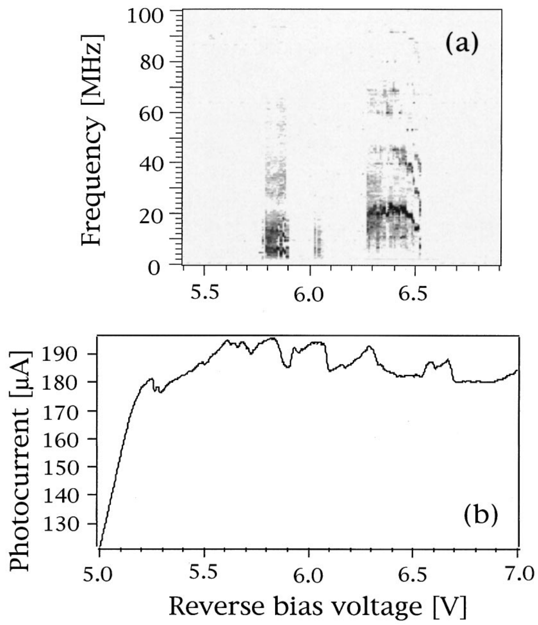

FIG. 2. (a) Frequency spectra of self-sustained PC oscillations and (b) the corresponding time-averaged PC-V characteristic for a laser intensity of 3.5 mW recorded at 20 K plotted on the same voltage scale. The darker areas in (a) correspond to larger amplitudes.

In order to study the temperature dependence of the electric-field distribution instabilities, we have investigated the oscillation behavior for a fixed laser intensity of 3.5 mW increasing the temperature. Figures 3(a) and 3(b) show the frequency spectra and time-averaged PC-V characteristic, respectively, recorded at 40 K. With increasing temperature, the full oscillatory window becomes wider again comparable

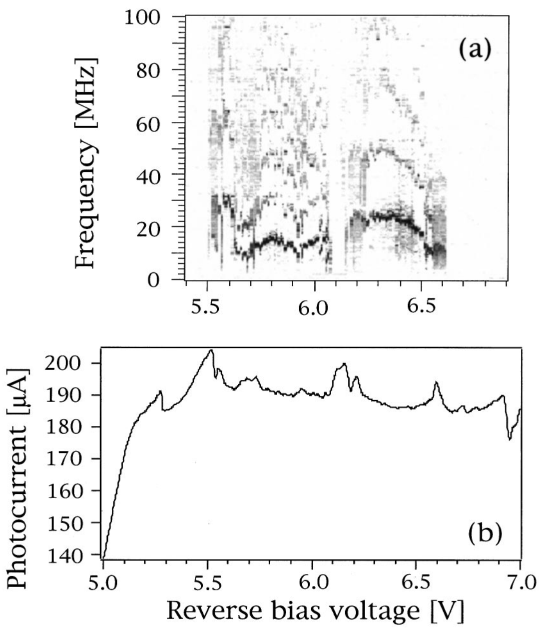

FIG. 3. (a) Frequency spectra of self-sustained PC oscillations and (b) the corresponding time-averaged PC-V characteristic for a laser intensity of 3.5 mW recorded at 40 K plotted on the same voltage scale. The darker areas in (a) correspond to larger amplitudes.

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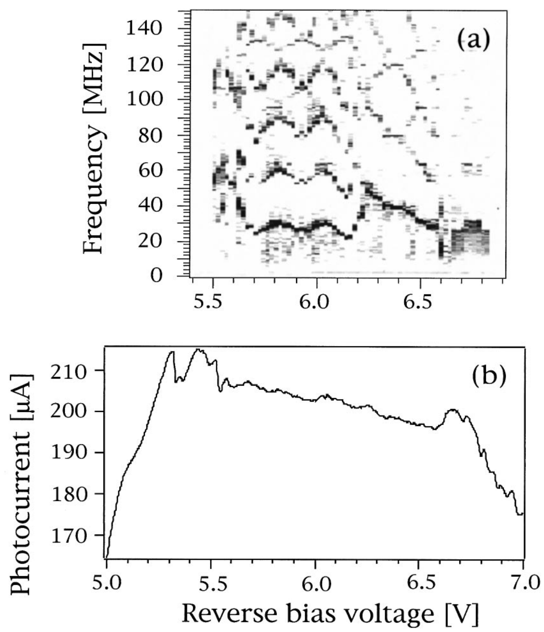

FIG. 4. (a) Frequency spectra of self-sustained PC oscillations and (b) the corresponding time-averaged PC-V characteristic for a laser intensity of 3.5 mW recorded at 60 K plotted on the same voltage scale. The darker areas in (a) correspond to larger amplitudes.

to the one in Fig. 2(a). At the same time, the static windows inside the full oscillatory window are reduced to one between 6.08 and 6.14 V, which is much narrower than the ones at 20 K. A further increase of the temperature to 60 K results in a complete disappearance of the static window as shown in Fig. 4(a). The full oscillatory window is slightly broadened reaching from 5.5 to 6.8 V.

Comparing the oscillatory behavior for the three different temperatures shown in Figs. 2–4(a), the oscillatory windows broaden, while the static windows become narrower as the temperature increases. At the same time, the fundamental oscillation frequencies exhibit a small increase. Furthermore, comparing the corresponding PC-V characteristic shown in Figs. 2(b)–4(b), the amount of fine structure within the full oscillatory voltage region decreases with increasing temperature. At 60 K, it almost disappears within the oscillatory window [cf. Fig. 4(b)]. These results clearly demonstrate that static domain formation at lower temperatures can be destroyed by thermal activation at higher temperatures resulting in dynamic domain formation, i.e., PC oscillations. These thermal activation effects can also be observed for other laser intensities above 3 mW. For example, as already mentioned above, this SL system does not show any oscillations in the whole voltage range for laser intensities above 8 mW at a temperature of 20 K. However, when the temperature is increased at this laser intensity, some oscillatory windows appear due to thermal activation.

A possible explanation of this thermal activation effect is that the carrier density necessary to quench moving domains into static ones may increase with temperature. This can be illustrated by considering the case of a doped SL,[11] for which static domains can be produced if the 2D doping density is larger than $N_0 = v_{min}\epsilon(F_{min} - F_{max})/[e(v_{max} - v_{min})]$. Here v_{max} (respectively v_{min}) is the maximum (respectively minimum) electron velocity at the plateau we consider, which is reached at the field F_{max} (respectively $F_{min} > F_{max}$). ϵ and e are the GaAs permittivity and the electron charge, respectively. While v_{max} and F_{max} are due to resonant tunneling processes, the minimum velocity is most sensitive to scattering processes, which become more active as the temperature increases. This can be quantified by numerical calculation of the sequential tunneling current as a function of an applied constant electric field [cf. Eq. (2) in Ref. 12], which is proportional to the effective electron velocity. Using the results of this calculation, we have checked that N_0 increases approximately linearly as the width of the GaAs scattering spectral functions increases. The precise nature of the scattering mechanisms that are dominant at each temperature and contribute to the broadening of the spectral functions was not considered in Ref. 12 and it should be the object of a separate study outside the scope of the present paper.

For an undoped SL, there is a laser intensity I_0, which plays the same role as the doping density N_0 above. To calculate it, we recall that PC oscillations stop when I_0 exceeds a critical value beyond which stable static domain formation is possible.[13] Simulations show that stable static domain solutions for a SL with N spatial periods have the following structure: a low-field domain (the electric field at the jth SL period is $F_j < F_{max}$ for $1 \leqslant j \leqslant n$) followed by a domain wall and a high-field domain ($F_j > F_{min}$ for $n+1 \leqslant j \leqslant N$). In this case $dv/dF > 0$ for all F_j. For doped and not illuminated SL's, this stability result can be proved rigorously.[11] To estimate the critical I_0, we notice that (as in the case of a doped SL) static domains can be constructed from a one-dimensional map: $F_{j-1} = f(F_j;\gamma,J) \equiv F_j - Jd/[\epsilon v(F_j)] + \gamma\tau_R e F_{max} v(F_j)/J$, $1 \leqslant j \leqslant N$ [cf. Eqs. (2.4) and (2.5) of Ref. 13 written in dimensional units]. $J, d, \tau_R,$ and $\gamma = \alpha I_0/(\hbar\omega)$ are the total current density in the SL, the SL spatial period, electron-hole recombination time, and photogeneration rate, respectively. ω is the laser frequency and α the absorption coefficient. The map $f(F;\gamma,J)$ has a three-branch shape similar to $v(E)$ for large enough γ. Then a stable static solution with low- and high-field domains exists if $f(F_{min},\gamma,J) \leqslant f(F_{n+1},\gamma,J) = F_n$: for the map f reaches its minimum at a field lower than F_{min} and fields on the third branch of v are always on the third *increasing* branch of f. The previous condition yields the inequality $(F_{min} - F_n)v_{min} \leqslant Jd/\epsilon - \gamma\tau_R e F_{max} v_{min}^2/J$. This is first satisfied for $F_n = F_{max}$ and $J = v_{max}(e\gamma\epsilon F_{max}\tau_R/d)^{1/2}$, the largest possible values for the low-field domain [see Eq. (2.3) of Ref. 13]. Inserting these values in the previous formula, we obtain an estimate of the critical I_0:

$$I_0 = \frac{\hbar\omega v_{min}^2 v_{max}^2 \epsilon (F_{min} - F_{max})^2}{ed\tau_R \alpha F_{max}(v_{max}^2 - v_{min}^2)^2}. \tag{1}$$

Again I_0 increases as the the minimum velocity increases. The previous arguments suggest that raising the temperature increases the width of the scattering spectral function. In turn this increases the minimum velocity. Thus, a greater laser intensity is required to stop current self-oscillations as the temperature increases.

An additional factor in the origin of the thermal activation effect is the in-plane diffusion of two-dimensional (2D) excitons in GaAs wells. Note that the spot diameter of the laser beam is about 20 μm, which is considerably smaller than the size of the diodes, which are squares with a side length of 50 μm. The temperature dependence of the mobility of 2D excitons was measured by Hillmer *et al.*,[14] who reported an increase of the mobility of 2D excitons with increasing temperature in the lower temperature regime, where it is dominated by interface roughness scattering. This effect probably reduces the density of photoexcited carriers inside the SL as the temperature increases. Since the electric-field distribution becomes dynamic and oscillations are generated, when the carrier density is not sufficiently large to achieve static domains, the reduction of the carrier density due to the thermally assisted diffusion of 2D excitons should result in a transition from static to dynamic domain formation. The time-averaged PC increases somewhat with increasing temperature, but this effect might originate from an increasing recombination lifetime. We conclude that the diffusion of photoexcited carriers in quantum wells may play an important role in destroying static domain formation. The destruction of static domains by thermal activation is easily observed by adjusting the laser intensity to values below 8 mW for which static and dynamic domains coexist. Since the unipolar mobility in 2D systems also depends on temperature,[15] domain formation in doped SL's may also be affected by thermal activation.

In conclusion, we have observed transitions between static and dynamic electric-field domain formation in an undoped, photoexcited GaAs/AlAs superlattice as a function of bias voltage. The oscillatory windows become narrower with increasing carrier density, and windows of static domain formation appear. The windows of static domain formation can be destroyed by an increasing sample temperature. Two mechanisms may explain the observed thermal activation process, but experiments to distinguish between these mechanisms are outside the scope of the present paper.

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