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Optically induced electric-field domains by bound-to-continuum transitions in *n*-type multiple quantum wells

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We report on the experimental evidence of electric-field domain formation induced by the intersubband photocurrent in *n*-type GaAs/Al$_x$Ga$_{1-x}$As multiple quantum wells. The domain structure manifests itself by a plateaulike regime in the voltage dependence of the total current under infrared illumination. Domain formation is caused by a negative differential field dependence of the photoexcited carrier mean free path. The domain structure does not exist in the dark since the increase of the thermally excited carrier density in the continuum overrides the decrease of the mean free path. [S0163-1829(98)51824-3]

Electric-field domains in semiconductor superlattices have been the topic of extensive research since the prediction of negative differential conductivity.[1] In weakly coupled *n*-type superlattices, negative differential conductivity (NDC) phenomena are caused by the transition from miniband conduction to nonresonant sequential tunneling[2] between adjacent quantum wells. These processes give rise to the formation of stable electric-field domains, where the low-field domain is characterized by miniband conduction and the high-field domain by sequential resonant tunneling between the first and second minibands of adjacent quantum wells.[3–5] In undoped superlattices, electric-field domains have also been induced by interband optical excitation.[6] In this case, the field distribution was studied directly via the Stark shift of the photoluminescence energy.

Electric-field domains also exist in bulk GaAs and other compound semiconductors. Propagating electric-field domains give rise to the Gunn effect, which is of importance for microwave oscillators.[7,8] Here the NDC is caused by intervalley scattering of electrons. The negative differential dependence of the drift velocity v_D as a function of the electric field F can be approximated by the expression[8,9]

$$v_D(F)=\frac{\mu_1 F+v_v(F/F_c)^4}{1+(F/F_c)^4}, \tag{1}$$

where μ_1 is the mobility at the Γ point, v_v the asymptotic drift velocity for $F\rightarrow\infty$, and F_c the characteristic field.

In this paper, we show that electric-field domains can also be induced by bound-to-continuum transitions in *n*-type multiple quantum wells (MQW's) under infrared optical illumination. In contrast to superlattice structures, negative differential conductivity is not caused by sequential resonant tunneling since the individual wells are separated by sufficiently large barrier layers. Instead, domain formation is due to a negative differential field dependence of the photoexcited carrier mean free path. No domains are found in the dark, since thermal carrier emission increases strongly with electric field, while the optical excitation rate is approximately constant.

We observe these effects in MQW structures optimized for bound-to-continuum transitions, which are widely used for infrared detection in the 8–12 μm atmospheric window.[10,11] While the behavior reported here is found to be typical for this class of layer structures, we concentrate in the following on a representative MQW structure containing $N=50$ *n*-type GaAs quantum wells (QW's), embedded between 48 nm thick Al$_{0.26}$Ga$_{0.74}$As barriers. The quantum wells are 4.1 nm thick and Si doped to a sheet concentration of 4×10^{11} cm^{-2} per well. The MQW is sandwiched between *n*-type contact layers. The sample was grown by molecular beam epitaxy on (100)-oriented, semi-insulating GaAs substrate and processed into mesa diodes of 0.014 mm^2 with Ohmic contact metalization.

Important information concerning the electronic transport properties is obtained from the *photoconductive gain* $g=L_c/L$, where L_c is the drift length of the carriers excited

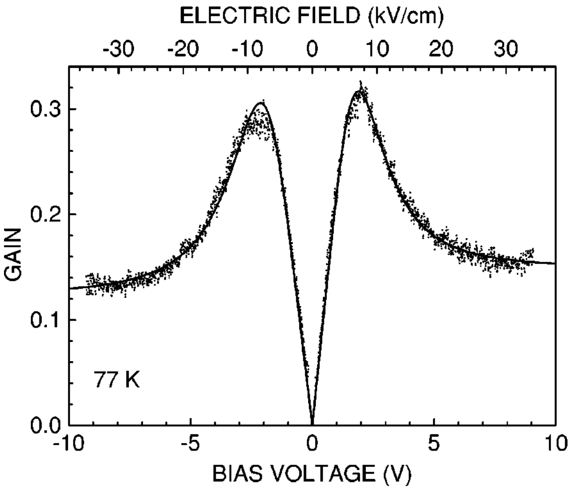

FIG. 1. Measured photoconductive gain g as a function of applied voltage and electric field. The solid line indicates a theoretical fit.

into the continuum before being recaptured by the QW's and $L = NL_p$ is the width of the MQW structure of period L_p. g is also accessible from the dark current I_D and its associated generation-recombination (G-R) noise i_{GR} within the bandwidth Δf. If $L_c \gg L_p$, i_{GR} is given by the relation[10,12]

$$i_{GR}^2 = 4geI_D\Delta f. \tag{2}$$

G-R noise represents the dominant noise contribution for the bound-to-continuum photocurrent since tunneling out of the QW ground state is negligible.

It has been shown previously[10,12] that thermally and optically excited electrons are in fact associated with identical gain values. In order to motivate this behavior, we note that the scattering length of electrons in the continuum is <100 nm, while the drift length L_c is >0.5 μm. Therefore, thermally and optically excited electrons in the continuum should have the same g since they are expected to have identical energy distributions.

We have measured the dark current noise i_N as a function of applied voltage V. The G-R noise is calculated via the relation $i_{GR}^2 = i_N^2 - i_J^2 - i_{AMP}^2$, which takes into account corrections due to the Johnson noise i_J, given by $i_J^2 = 4k_BT(dI_D/dV)\Delta f$, and due to the measured amplifier noise i_{AMP}. The field dependence of g is plotted in Fig. 1. Reliable values of g are obtained at electric fields down to about ± 1 kV/cm. At fields above ± 8 kV/cm, g exhibits a pronounced negative differential behavior. This negative differential dependence is expected to induce NDC in the case of a constant carrier density in the continuum.

It is instructive to relate the measured gain with the drift velocity. Using the relation $g = v_D\tau_c/L$ and assuming a constant capture time τ_c, we have used Eq. (1) in order to obtain a numerical fit to the measured data in Fig. 1. The fit yields $F_c = 8.0$ kV/cm (9.3 kV/cm) for positive (negative) polarity, $v_v\tau_c = 0.40$ μm (0.32 μm), and $\mu_1\tau_c = 1.57$ μm^2 (1.35 μm^2). Since this value of F_c is only twice as large as in bulk GaAs,[8,9] it is plausible that the observed decrease of g is indeed caused by intervalley scattering. As indicated in Fig. 2(a), the L minimum of $Al_{0.26}Ga_{0.74}As$ lies slightly below the X minimum,[13] such that the Γ-X transfer is expected to be as efficient as the Γ-L transfer due to the large density of states at the X minimum.

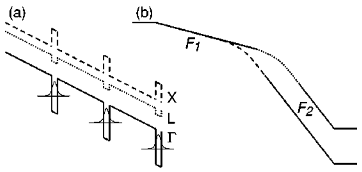

FIG. 2. (a) Potential distribution of the Γ, L, and X minima of a $GaAs/Al_{0.26}Ga_{0.74}As$ MQW structure. (b) Schematics of high- and low-field domains, showing the translation of the transition region (indicated by the dashed and dotted lines, respectively) upon changing the bias voltage.

Concerning the capture time τ_c and its field dependence, we note that $\tau_c \approx 6$ ps at $F = 0$ has been predicted previously for similar MQW structures.[12,14] For $F > 0$, $\tau_c < 7$ ps has been obtained in recent time-resolved photocurrent measurements.[15] We therefore expect that τ_c changes only slightly with field. Estimating τ_c to a value of about 5 ps, our fit allows us to determine the mobility and the saturation drift velocity of the electrons in the continuum above the $Al_{0.26}Ga_{0.74}As$ barriers. We find $v_v = 7.9 \times 10^6$ cm/s (6.5×10^6 cm/s for negative polarity) and $\mu_1 = 3100$ cm^2/V s (2700 cm^2/V s). v_v has a similar value as typically observed in bulk GaAs, while μ_1 is about three to four times smaller. The lower value of μ_1 (as compared to bulk GaAs) is in good correspondence with the observed higher value of F_c. The noise gain in Fig. 1 shows a slight asymmetry with respect to the polarity of the bias, which is attributed to an asymmetric distribution of the dopant atoms with respect to the well centers.[10,16]

Let us now turn to the conduction properties under optical illumination. Figure 3(a) summarizes current-voltage (I-V) measurements under illumination with 9.2 μm radiation from a CO_2 laser. All curves show a linear I-V characteristic for $|V| < 1.0$ V. For $|V| > 1.4$ V, we observe a characteristic plateau behavior in the regime where the photocurrent is much higher than the dark current. Again, there is a slight dependence on the polarity of the bias, which is explained by an asymmetric dopant distribution.

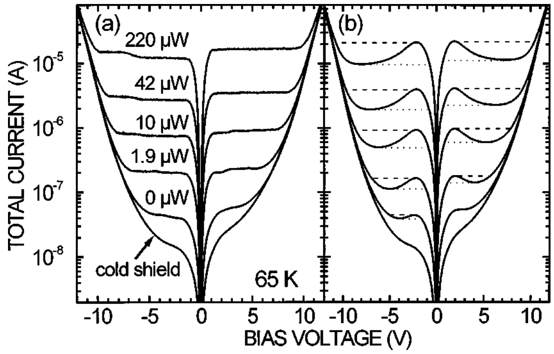

FIG. 3. Total current vs applied voltage at different incident powers as indicated, (a) as measured, (b) as expected in the case of a constant electric field across the MQW structure (full lines). The expected I-V behaviors in the case of domain formation at the peak and valley current values, respectively, are indicated in (b) by dashed and dotted lines.

In order to understand the physics behind the observed plateau behavior, we express the current density $I(F)$ as $I(F)=e[n_{th}(F)+n_{opt}]v_D(F)$, where we have introduced the thermally and optically excited carrier densities n_{th} and n_{opt}, respectively. Using the conventional definition[10,12] of the responsivity (the photocurrent per incident power), $R=e\eta g/h\nu$, we have $en_{opt}v_D=e\eta gP/h\nu$. Here η is the quantum efficiency, P the power density, and $h\nu$ the photon energy. We thus obtain

$$I(F)=e\left[n_{th}(F)\frac{L}{\tau_c}+\frac{\eta P}{h\nu}\right]g(F). \tag{3}$$

Since η is approximately constant ($\eta\approx6\%$ for the present excitation conditions), the field dependence of g will give rise to a pronounced NDC for strong enough illumination. We note that τ_c does not enter explicitly into the photoinduced component, such that a possible field dependence of τ_c just enters into the thermal current.

It can be seen in Fig. 3(a) that the dark current increases strongly with applied voltage. Due to this strictly positive conductivity, domain formation cannot occur in the dark. This behavior is due to the fact that the negative differential dependence of $g(F)$ is overridden by the field dependence of the term n_{th}/τ_c. At the higher fields, the prominent increase of $n_{th}(F)$ is attributed to the field-induced reduction of the effective barrier height, which increases n_{th} because of the Fermi distribution inside the QW's.[10]

The *I-V* curves as expected from Eq. (3) in the case of a *spatially constant* electric field across the MQW are shown in Fig. 3(b) (full curves). The curves are obtained by adding suitable multiples of the fit function for g (see Fig. 1) to the experimental dark *I-V* curve. This procedure results in a pronounced NDC under illumination.

In the NDC regime, this configuration is not stable, and the field distribution splits up into low-field and high-field domains, characterized by the fields F_1 and F_2, respectively. Here current conservation requires that $I(F_1)=I(F_2)$, which is possible in the regimes indicated by the dashed and dotted lines in Fig. 3(b). Under isotropic conditions along the growth direction, the high-field domain increases at the expense of the low-field domain when the voltage across the whole structure is increased, as indicated in Fig. 2(b). In this case, the current remains constant, which explains the plateaus in the experimental *I-V* curves of Fig. 3(a).

The precise value of the plateau current at a given incident power depends on the details of the transport mechanism, which determines the transition region between the two domains [see Fig. 2(b)]. Let us assume for the moment that n_{th} and n_{opt} are proportional to the total carrier density n_0, and that diffusion effects and displacement currents are not present. Under these assumptions, Poisson's equation $dF/dx=\rho/\epsilon$ requires that a negative space charge $\rho(x)$ is present at the transition region. Such a situation only exists if the current equals the peak current before the NDC regime, such that the plateaus will be given by the dashed lines in Fig. 3(b).

In reality, the situation is expected to become more complicated due to the details of the transport mechanism in the MQW structure. It has been shown recently by Kwok *et al.*[17] within a rate equation approach that domain formation in weakly coupled superlattices occurs at currents that are significantly below the peak current. We expect a similar reduction to occur when taking into account the microscopic structure of the MQW, such that the resulting plateau value will be located between the peak and valley currents [dashed and dotted lines in Fig. 3(b)].

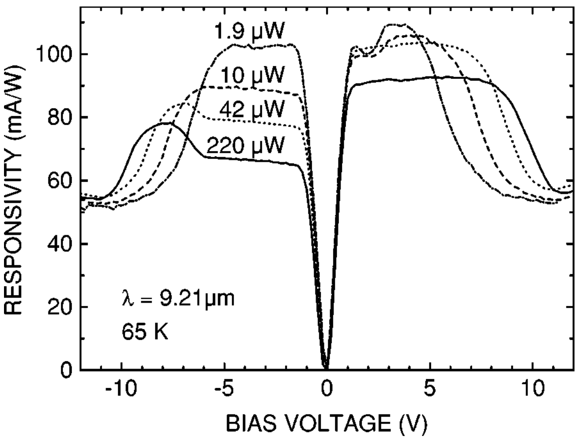

FIG. 4. Photocurrent responsivity at 9.2 μm illumination wavelength vs applied voltage at different power levels as indicated.

We have also measured the bias dependence of the responsivity R using the methods of Ref. 18. As summarized in Fig. 4, we observe an approximately linear increase of R at small bias, a regime with a pronounced plateaulike structure at intermediate bias, followed by a decrease at high bias. The general behavior can be understood by taking the difference between the curves of Fig. 3(a) with and without illumination. In particular, due to the nonmonotonic electric field, the decrease of R toward high bias is different from the negative differential behavior of g in Fig. 1. In fact, this decrease originates from an increase of the dark current that has been subtracted from the total current, rather than from a decrease of g. At the highest bias voltages [above ±11 V in Fig. 3(a)], the dark current is much larger than the photocurrent. Therefore, we obtain again a constant field across the MQW, such that R does not depend any more on P (see Fig. 4).

The measurement of Fig. 4 also reveals some features which cannot be explained within our previous theoretical approximations. First, the plateau value of R decreases systematically with increasing incident power. This decrease can be explained by assuming that the plateau is located significantly below the peak current, similar to the observations in Ref. 17. Second, an additional structure appears at certain power levels (at 1.9 μW and 32 μW for positive polarity, and at 42 μW and 220 μW for negative polarity). Related structures are also visible in Fig. 3(a), where they correspond to a slight steplike increase of the total current. The origin of these steps is not quite understood at present. As a tentative explanation, we take into account a fine structure in the field dependence of the transport behavior, induced by resonant alignment between above-barrier states[19] and/or by Stark localization of the minibands at higher energies.

We point out that the observed decrease of R with increasing power is different from the nonlinearity discussed in

Ref. 18. There the nonlinearity originates from the voltage drop at the emitter barrier. This voltage drop increases upon optical illumination since bound-to-continuum excitation is negligible at the GaAs contact. Therefore, the field across the active MQW region is reduced, such that R decreases at small bias voltages ($|V|<1$ V in Fig. 4). When domain formation has occurred, this voltage drop at the emitter barrier just influences the domain sizes, while the photocurrent remains constant. We also note that the nonlinearity associated with domain formation is very small. It has a similar magnitude as observed in our previous work,[18] such that it is negligible in the context of thermal imaging.[10,11]

In conclusion, we have found experimental evidence of domain formation induced by bound-to-continuum transitions in multiple quantum well structures. The phenomenon is caused by a decrease of the photoconductive gain with increasing electric field, caused by intervalley scattering of the electrons in the continuum. Since the observed phenomenon is analogous to the Gunn effect, it will be interesting to look for current oscillations in these structures. In spite of the negative differential mobility, the electric field remains homogeneous in the dark, such that MQW structures can be used as a model system to investigate intervalley scattering in III-V semiconductors.

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