Electro-optical multistability in GaAs/AlAs superlattices at room temperature

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We have studied the optical absorption properties of a GaAs/AlAs short-period superlattice at room temperature in an electric field perpendicular to the layers. Several pronounced optical transitions related to Wannier–Stark localization are observed indicating a coherence length of at least five superlattice periods. These transitions produce multiple regions of negative differential photoconductivity which are used to realize a multistable self-electro-optic effect device.

Recently, there has been an increasing interest in the optical properties of semiconductor superlattices (SLs) in which the spatial localization of the carrier states can be tuned by applying a vertical electric field F.[1–5] This so-called Wannier–Stark localization is accompanied by a splitting of the minibands of the SL into ladders of evenly spaced energy states with an energy separation of eFd, where d is the SL period. These Wannier–Stark states are still delocalized over a few SL periods so that optical transitions between electron and hole states centered in different wells are possible. A spatial separation of n SL periods thus results in an energy shift of $neFd$ with respect to the spatially direct $(n = 0)$ transition. This feature has been observed in photocurrent,[1] electroreflectance,[2] transmission,[3] and resonant Raman spectroscopy[4] experiments. All these studies were performed on GaAs/Al_xGa_{1-x}As (x about 0.3) and $Al_{0.24}Ga_{0.24}In_{0.52}As/Ga_{0.47}In_{0.53}As$ superlattices. The observation of Wannier–Stark localization in GaAs/AlAs SLs at low temperature has recently been reported.[6]

When the electric field is increased, holes are usually much more strongly localized than electrons due to the difference in the effective masses. It is thus a good approximation to consider the valence states to be localized within one SL period. The absorption strength I_n of the transition between a completely localized hole state and an extended electron state has been calculated in Ref. 7. The result is $I_n \propto [(\Delta/2eFd)^n/(n!)]^2$, where Δ is the width of the miniband at zero field. Applying Stirling's formula, one gets the illustrative approximation $I_n \propto (2\pi n)^{-1}[\exp(1)\Delta/2neFd)]^{2n}$, which implies that the Wannier–Stark ladder states are extended over approximately $\Delta/neFd$ SL periods.[1,6,7] The maximum value of n up to which transitions between these states can be resolved is limited by the coherence length of the carriers which is influenced by impurity scattering and by small fluctuations in layer thickness or alloy composition. Values from $n = -6$ to $n = +3$ have recently been reported[8] for a 2 nm/4 nm GaAs/$Al_{0.35}Ga_{0.65}$As superlattice indicating a low-temperature coherence length of at least 60 nm.

At room temperature, Wannier–Stark localization is of interest in the context of electro-optical modulators as well as self-electro-optic effect devices (SEEDs).[9] Very recently, Bar-Joseph *et al.* have demonstrated SEED operation using a 3 nm/3 nm GaAs/$Al_{0.3}Ga_{0.7}$As superlattice.[5] Room-temperature electroabsorption in superlattices has been reported by Yan *et al.*[10]

In this letter we report on the first investigation of Wannier–Stark localization in the GaAs/AlAs system at room temperature. We clearly observe in our experiments several spatially indirect heavy-hole-like (from $n = -4$ to $n = +1$) transitions and also the $n = -1$ light-hole-like transition indicating a coherence length of at least five SL periods (21 nm) at room temperature. Our device exhibits up to four regions of negative differential photoconductivity which are used to achieve multistable SEED operation.

The binary-binary GaAs/AlAs superlattice is a very promising system for high performance SEEDs based on Wannier–Stark localization since compositional fluctuations and interface roughness are minimized. Additionally, field-induced complete carrier localization can still be achieved for much smaller SL periods than for the GaAs/$Al_{0.3}Ga_{0.7}$As case due to the large potential steps at the GaAs/AlAs interfaces. In particular at room temperature where the coherence length is reduced by phonon scattering, this gives rise to a large ratio between the coherence length and the period of the SL.

Our measurements were performed with an undoped SL consisting of 40 periods of 3.2 nm GaAs and 0.9 nm AlAs. The SL is sandwiched between 800-nm-wide $Al_{0.33}Ga_{0.67}$As window layers which are n doped at the substrate side to 1×10^{18} cm^{-3} and p doped at the top side to 1×10^{19} cm^{-3}. The whole p-i-n diode structure was grown by molecular beam epitaxy on a (100) oriented n^+-GaAs substrate and processed into mesas of 450 μm diameter. Ohmic contacts were provided by evaporation of Cr/Au (top side) and AuGe/Ni (substrate side).

The photocurrent spectra were obtained with a halogen lamp and a double monochromator. The photocurrent which was in the nA range was measured with a lock-in amplifier and corrected for the spectral dependence of the excitation source. A series of room-temperature spectra is plotted in Fig. 1. We observe well-pronounced $n = +1$,

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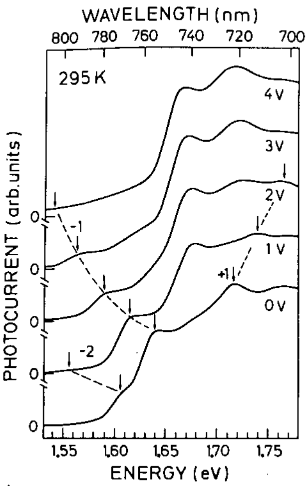

FIG. 1. Photocurrent spectra at different external reverse bias. The $n = +1$, $n = -1$, and $n = -2$ heavy-hole transitions are indicated by arrows.

$n = -1$, and $n = -2$ heavy-hole-like transitions which shift in energy by about *neFd*. Even the $n = -1$ light-hole-like transition is clearly resolved at 1.62 eV for 3 V reverse bias. The $n = 0$ heavy-hole- and light-hole-like transitions (at 1.67 and 1.72 eV, respectively) gain oscillator strength with increasing electric field due to Wannier–Stark localization[6,11] and undergo a very slight red shift according to the quantum-confined Stark effect.[12] The voltage drop per SL period is easily calculated from the total (applied plus built-in) voltage and the number of periods in the sample. The built-in voltage is determined below.

Figure 2 shows static current-voltage curves obtained with a picoampere meter (HP 4140B). The dark current in reverse direction is caused by thermal excitation of carriers across the band gap of the SL and increases nearly exponentially with the reverse bias. It freezes out completely ($< 10^{-13}$ A) when the temperature is decreased. The reverse breakdown voltage at room temperature is 10.3 V. It is important to note that, under forward bias, diffusion of thermal carriers into the SL region already produces some dark current in forward direction before the built-in voltage is reached.

Weak illumination of a few nW power is already sufficient to produce negative differential conductivity at external voltages where the dark current is in the pA regime. This is illustrated in Fig. 2 for the wavelengths of 758 and 765 nm where we see one and two regions of negative differential

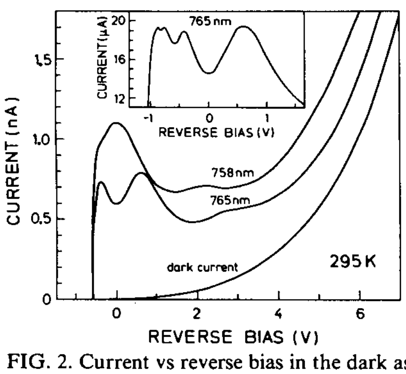

FIG. 2. Current vs reverse bias in the dark as well as for 758 and 765 nm illumination of a few nW. The inset corresponds to 300 mW illumination at 765 nm.

photoconductivity, respectively, which are caused by the energy shift of the $n = -1$ and $n = -2$ heavy-hole-like transitions. The weaker structure at a reverse bias of 2.2 V (758 nm) and 2.6 V (765 nm) is produced by the $n = -1$ light-hole-like transition. The cutoff at about 0.6 V forward bias is due to the diffusion current mentioned above.

Additional regions of negative differential conductivity are resolved at higher illumination levels where the relative importance of the diffusion current is smaller. The inset of Fig. 2 shows the current-voltage characteristics under 300 μW illumination at 765 nm using a dye laer. The interesting result is that there are now four peaks in the current-voltage characteristics which correspond to the $n = -1$ to $n = -4$ heavy-hole-like transitions. It might be possible that even more transitions can be resolved since the expected position of the $n = -5$ transition is still masked by the diffusion current. We note that multiple negative differential conductivity was also observed in a different SL stucture due to an interplay between tunneling resonances and space charge.[13] In the present system, however, the coupling between wells is much stronger so that space-charge effects are not expected to play a significant role. Multiple negative differential absorption due to Wannier–Stark localization has been predicted in Ref. 7.

The built-in voltage (about 1.1 V) of the sample corresponds to the bias at which the photocurrent under strong illumination becomes negative (inset of Fig. 2). We note that the small photocurrent efficiency (0.07 A/W) is mainly determined by losses due to metallic-like reflection at the highly doped top contact. The estimated maximum absorption of our sample close to the SL band edge is 15–30% corresponding to an absorption length of 0.5–1 μm. The data of Fig. 2 indicate that the absorption length can be modulated by a factor of 2. For the purpose of modulation of transmitted light, the window layers should be doped only slightly in order to minimize the reflection losses. The desired contrast ratio can be adjusted by the total thickness of the SL. Clearly, a large contrast ratio requires a thick SL layer which, on the other hand, reduces the total transmission of the modulator.

The appearance of the $n = +1$ to $n = -4$ transitions indicates that the room-temperature coherence length of the electrons at low electric fields is at least five SL periods, i.e., 21 nm, and decreases to one SL period at high fields. This result strongly favors the all-binary GaAs/AlAs material system with its superior interface quality for the fabrication of electro-optical devices based on Wannier–Stark localization. Due to the large band offsets (about 1 eV at the Γ point[14]), it is possible to design a specific SL band structure at a significantly smaller period than, e.g., for the GaAs/$Al_{0.3}Ga_{0.7}As$ system. At room temperature, this is particularly advantageous since the coherence length of the carriers is additionally reduced by phonon scattering which is not so sensitive to the material parameters.

In the context of transport, the coherence length should be of the same order as the mean free path l_s for LO phonon scattering, provided that the drift velocity v_d is close to the saturation limit. Assuming a momentum relaxation time τ_p of about 100 fs,[15] the relation $v_d = l_s/\tau_p$ yields drift velocities up to 2×10^7 cm/s at moderate fields ($F<10$ kV/cm) decreasing down to about 4×10^6 cm/s at the highest fields. This rough estimate corresponds to transit times of 1.1–4.2 ps across the SL region of the present sample.

We will demonstrate next how these regions of negative differential conductivity can be used to obtain multistable SEED operation. For this purpose, we have connected a load resistor in series to the sample (inset of Fig. 3) and swept the laser power. In Fig. 3 the photocurrent is plotted versus the optical power. At a wavelength of 758 nm we observe switching between two stables states. At 765 nm illumination there exists a region where three stable states are possible (shaded region in Fig. 3). The arrows indicate how the different branches can be reached.

It is expected from the appearance of the $n=-3$ and $n=-4$ transitions that configurations with four and five stable states can also be realized. The use of the load resistor, however, gives rise to some noise due to intensity fluctuations of the dye laser which makes it difficult to observe switching between states coexisting in a very narrow regime. Much more stable SEED operation can be achieved by replacing the load resistor by a second photodiode which is also operated in reverse direction as proposed by Miller *et al.*[16] In this case, both photodiodes act on intensity fluctuations in the same way so that the voltage across each diode remains constant.

Similar to conventional SEEDs,[9] the load resistance R_V is inversely proportional to the optical power at which the switching takes place. The time required for switching is approximately given by R_VC, where C is the sample capacitance. Hence, the amount of energy which is necessary for switching the device is basically independent of R_V and amounts to a few nJ. Due to the strong coupling between the wells of the superlattice, the vertical transport of carriers proceeds too fast to produce any significant effect on the switching times. A further reduction of the switching time can be achieved by decreasing the capacitance. This would also reduce possible distortions from "diffusive" conduction along the doped layers of the *p-i-n* structure[17] which become particularly important if the sheet resistivity of the doped layers is large.

In summary, we have reported on the first room-temperature study of Wannier–Stark localization in short-period GaAs/AlAs superlattices. Our structure with 3.2 nm wells and 0.9 nm barriers shows spatially "indirect" transitions (from $n=-1$ to $n=-4$) and several regions of negative differential photoconductivity at room temperature. We have used these regions to demonstrate optical multistability and switching. Our experiments clearly reveal that the GaAs/AlAs system is of superior quality for the fabrication of high performance electro-optical devices based on Wannier–Stark localization.

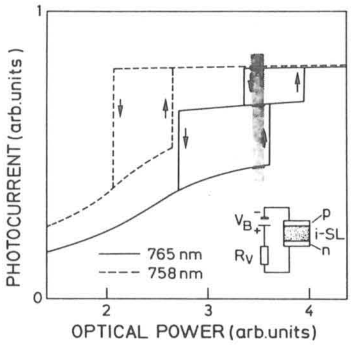

FIG. 3. Photocurrent vs illumination power (100 μW range) for 758 and 765 nm illumination at room temperature. The switching is indicated schematically; the arrows refer to its direction. The experimental circuit is displayed in the inset ($V_B=6$ V, $R_V=1$ MΩ). The shaded area marks the region of switching between three stable states at 765 nm.

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