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# Franz–Keldysh effect in a two-dimensional system

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We report luminescence and photocurrent experiments on an InGaAs/GaAs quantum well in strong lateral electric fields. The fields are imposed with an interdigitated gate on the crystal surface that consists of an array of metal stripes with a 250 nm period. The small period allows generation of electric fields of about $10^5$ V/cm by application of only 1.5 V at the gate electrodes. Strong subgap absorption and oscillations of the interband absorption as function of radiation energy are observed and discussed in view of the Franz–Keldysh effect. The resulting photo-$I$-$V$ characteristic shows high potential for electro-optic applications.

Great interest in optical computing and the need for ultrafast telecommunication techniques have triggered the development of various devices for modulation, detection, and all-optical switching.[1] A large family of these devices, based on layered semiconductor structures, make use of the fact that strong electric fields modify the optical properties. Generally, in these devices the electric fields are applied *along the growth direction*, i.e., along the direction in which the crystal properties are modulated.[2–4] In modulation doped so-called $n$-$i$-$p$-$i$ structures the effective band gap is reduced due to spatially indirect transitions[5] by an amount that can be field-effect tuned by voltages applied between $n$- and $p$-doped layers.[2,6] An electric field applied perpendicular to a quantum well results in the so-called quantum confined stark effect.[7] Here, again, spatially indirect transitions, but also field-effect modified confinement and—in case the well starts to be occupied by electrons—band-gap renormalization and phase space filling tune the effective band gap.

In this letter we study the optical properties of a single InGaAs quantum well in electric fields with large components in the lateral direction, i.e., *perpendicular to the growth direction.* We demonstrate very similar electro-optic effects to the ones mentioned above in a device fabricated on a rather simple layer sequence and operating at low voltages. The electric field is induced by an interdigital front-gate electrode. To avoid hot carrier effects, the voltages are applied over narrow gaps that repeat periodically across the area of the laser spot. The metal stripes form two interlocked finger gates as depicted in Fig. 1. This allows to achieve fields of the order of $10^5$ V/cm with a voltage difference ($\Delta V$) of only 1.5 V applied between the two finger gates. At these fields, the absorption spectra experience strong modifications. With increasing field, we observe an effective narrowing of the band gap and oscillations in the absorption which are well known in the case of bulk semiconductors as Franz–Keldysh effect.[8,9] We observe this effect for the first time in a quantum well sample.

The devices were fabricated from a single quantum well sample grown by molecular beam epitaxy (MBE) on a GaAs substrate. The quantum well consists of 10 nm of pseudomorphic $In_{0.15}Ga_{0.85}As$ grown on a 1 $\mu$m GaAs buffer and is covered by a 20 nm GaAs cap layer. The interdigital gate electrode with 100 nm stripes and 150 nm pitches is fabricated by evaporating 300 Å titanium through a polymethylmethacrylat mask defined by electron beam lithography and a subsequent lift-off step. The sample layout and gate geometry is shown schematically in Fig. 1. The total active area of the gate is $200\times200$ $\mu m^2$, which is a typical laser spot size in our experiments. If a voltage $\Delta V$ is applied between the two finger gates, a type II lateral superlattice potential with period $a=500$ nm is induced at the location of the quantum well as indicated on the right-hand side of Fig. 1. We estimate that approximately $\exp(-2\pi\cdot d/a)\approx73\%$ of the externally applied potential modulation is still present at the location $d=25$ nm of the quantum well below the surface, which is verified by a numerical solution of Poisson's equation for our sample and gate geometry. The calculation also reveals that the lateral field strength in the pitches between the gate fingers is fairly homogeneous.

The resistance between the finger pairs typically is a few M$\Omega$ at room temperature and increases to $R>1$ G$\Omega$ at $T\leqslant10$ K both in the dark as well as under subgap illumination. Illuminated with light of energies above the band gap the resistance depends on both the intensity and the energy of the radiation which we employ to measure the absorption as discussed below. We use a titanium-sapphire laser pumped by an argon-ion laser as radiation source. The samples are kept at temperatures below 10 K.

In Fig. 2(a), a photoluminescence excitation spectrum

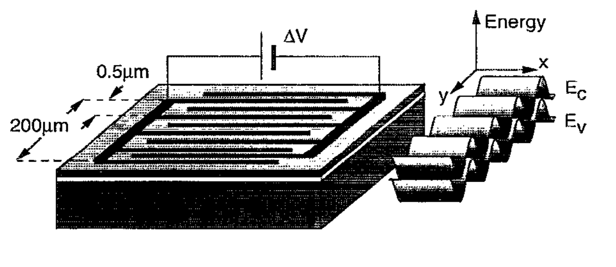


FIG. 1. Sketch of the sample and gate geometry (not to scale). The quantum well located 20 nm beneath the gate is indicated by a white line. On the right-hand side the conduction and valence band edges in the lateral type II potential superlattice induced by a finite gate voltage $\Delta V$ are indicated.

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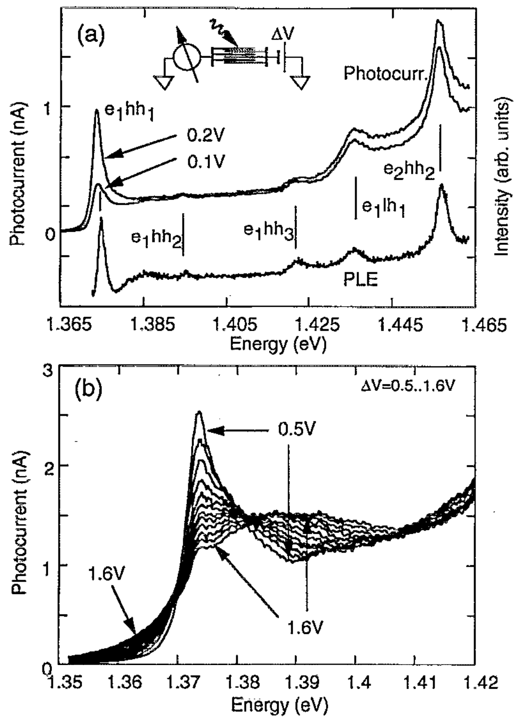

FIG. 2. (a) Two photocurrent spectra measured with gate voltages $\Delta V=0.2$ and 0.1 V, respectively (left scale). The third trace is a photoluminescence excitation spectrum recorded with similar laser intensity on a spot of the sample that is not covered by a gate (right scale). The inset indicates the experimental setup for photocurrent measurements. (b) Photocurrent spectra recorded at various gate voltages between $\Delta V=0.5$ V and $\Delta V=1.6$ V. The excitation intensity is 20 nW.

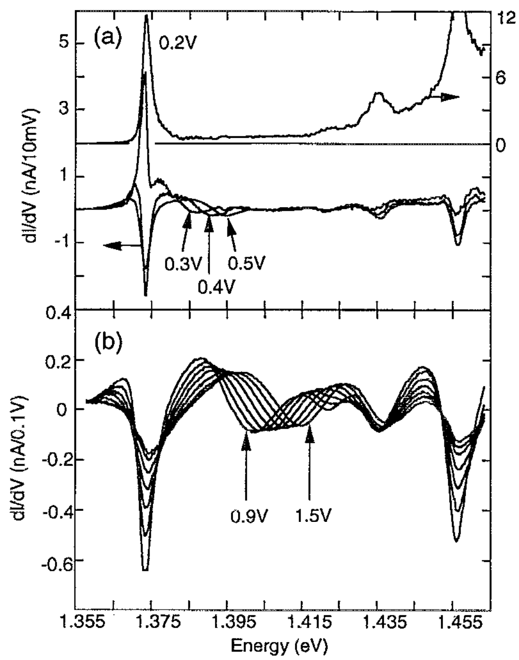

FIG. 3. Gate voltage derivatives of photocurrent spectra recorded at gate voltages (a) between $\Delta V=0.2$ V and $\Delta V=0.5$ V and (b) $\Delta V=0.9$ V and $\Delta V=1.5$ V.

recorded on a part of the quantum well sample that is not covered by the gate is compared to photocurrent spectra measured between the finger gates as depicted in the inset. All the excitonic features are seen in both the photocurrent and the photoluminescence excitation spectra. The structure in the photocurrent obviously arises from the rate of photocarrier generation in the well and is thus determined by the absorption of the quantum well.

Note, however, that in contrast to the higher excitonic transitions the $e_1hh_1$-exciton peak develops to its full strength only at voltages above $\Delta V=0.2$ V. A related behavior is observed in the photoluminescence signal of the sample. Whereas at $\Delta V=0$ V a strong luminescence peak is observed at an energy of 1.371 eV, the photoluminescence emission decreases rapidly at voltages around $\Delta V=0.2$ V. At $\Delta V \geqslant 0.4$ V only a weak luminescence remains with 18% intensity of the emission signal at $\Delta V=0$ V. This signal no longer changes with gate voltage and occurs at the same position (1.372 eV) as the luminescence measured on parts of the quantum well aside the gate region. This suggests that above $\Delta V=0.4$ V the luminescence stems from areas without gate that are not intentionally illuminated.

The electric field necessary to ionize excitons is approximately given by the exciton binding energy divided by the effective Bohr radius: $E_x/(ea_B^*) \approx 10$ mV/100 Å$=10^4$ V/cm. This field is present in the quantum well at $\Delta V \approx 0.2$ V. We thus conclude that the luminescence is quenched because field ionization of excitons acts as a competing nonradiative channel similar to observations in bulk GaAs.[10] At the same lateral field strength the first exciton peak in the photocurrent spectrum is enhanced because even carriers excited coldly into this state now can dissociate and contribute to the photocurrent.

The effect of high in-plane fields on the absorption is illustrated in the spectra of Fig. 2(b). Here, the externally applied voltages range from 0.5 to 1.6 V in steps of 0.1 V. The fine ripple is due to Fabry–Perot effects. With increasing gate voltage the $e_1hh_1$-excitonic peak of the photocurrent diminishes whereas the photocurrent signal extends increasingly to lower energies in the subgap region.

Clear oscillations are resolved in the modulation spectra of Fig. 3. Here, we superimpose a small (0.1–0.01 V) alternating voltage onto the gate voltage $\Delta V$ and directly measure the gate voltage derivative of the photocurrent with lock-in technique. At $\Delta V=0.2$ V the modulation spectrum is positive over the entire energy range, i.e., the photocurrent grows with the gate voltage at all excitation energies. At $\Delta V=0.3$ V the field induced modification of the absorption becomes so large, that the signal becomes negative at certain energies. At $\Delta V \geqslant 0.3$ V oscillations appear on the high energy side of the $e_1hh_1$-excitonic peak in an energy region that cannot be assigned to any excitonic transition of the quantum well. The spectra in Fig. 3(b) are recorded in an extended voltage range and demonstrate that the oscillation period increases with increasing field. These oscillations, analogous to the bulk Franz–Keldysh effect[8,9] and predicted theoretically for two-dimensional systems,[11] were not observed in an earlier attempt to measure in-plane electro-optic effects.[12] Presum-

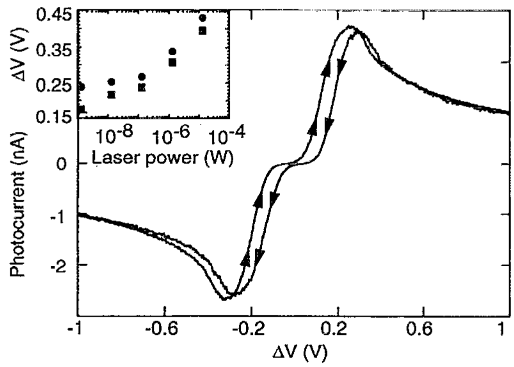


FIG. 4. Photocurrent recorded as function of the gate bias $\Delta V$ at an excitation energy of 1.3735 eV and 1-$\mu$W intensity. Arrows mark the direction in which the traces were recorded. The inset presents the photocurrent peak position as function of the excitation energy. Circles denote the peak position at forward sweep, squares those recorded in the reversed sweep.

ably, this is caused by the material system used in those experiments. In the GaAs/AlGaAs system the light-hole heavy-hole splitting is much less pronounced than in our strained system so that the heavy-hole oscillations in GaAs/AlGaAs are obscured by strong light-hole features. We should point out that from this point of view our system is exceptionally well suited for the presented studies.

Qualitatively, our observations show very good agreement with what is expected for the Franz–Keldysh effect. Also, the period of the oscillatory structure that can be resolved in the photocurrent as function of energy is of the same order of magnitude as the one expected for the Franz–Keldysh effect. However, a more quantitative analysis of our data has not been attempted yet, since the solutions of the problem have to be found numerically. The Franz–Keldysh effect for lateral fields in two-dimensional systems has been considered by Ledermann and Dow.[11] There numerical results are presented only for the quantity $[\alpha(F)-\alpha(0)]$ with $\alpha$ being the absorption coefficient and $F$ the electric field, whereas we measure $\partial\alpha/\partial F(F)$. We note in addition, that unlike the situation considered in Ref. 11 here the potential forms a type II superlattice so that the states involved in the transitions are distinct from those in Ref. 11 because one-dimensional subbands or minibands are formed.

The above effects result in an interesting $I$-$V$ curve of the device, when illuminated with light of the energy of the $e_1hh_1$ exciton. The $I$-$V$ curve in Fig. 4 is recorded with illumination at 1.3735 eV and intensity of 1 $\mu$W. The current grows with the applied voltage up to the point, where the field ionization threshold of the exciton is reached and decreases from there on due to the diminishing excitonic absorption. Very similar $I$-$V$ characteristics as well as the voltage tunability of the absorption are the key features necessary for the operation of self-electro-optic-effect devices (SEEDs).[13] From this analogy we imply that our device shows potential for use in all the circuit applications demonstrated previously with SEEDs.[3,4] The small capacitance, the ease of fabrication, and the geometry (e.g, a periodic index modulation *perpendicular* to a waveguide structure is possible) distinct from existing devices could be advantageous in certain applications.

The inset of Fig. 4 shows the voltage position of the peak current as a function of incident laser power. This position corresponds to a fixed value of the electric field at the quantum well, that is given by the field ionization threshold of the exciton. Hence the inset of Fig. 4 indicates, that at higher illumination intensity the potential modulation of the gate is partly screened by photogenerated carriers similar to observations in $n$-$i$-$p$-$i$ structures[5] and quantum wires,[14,15] where the smoothening of the potential modulation by photoinduced carriers shifts the luminescence signal to higher energies. At this point it is not clear whether free carriers accumulating in the well beneath the metal stripes or photoinduced charge transfer into surface states is responsible for the screening effect. Accumulation of free carriers might allow the generation of a cold electron-hole plasma in a release pulse triggered by rapidly short circuiting the finger gates.

Charge accumulation of photoinduced carriers that partly screen the potential could also be responsible for the hysteresis of the $I$-$V$ curve in Fig. 4. The arrows in the traces of Fig. 4 denote the direction in which the traces were recorded. If the peak current is approached from low voltages that do not suffice to ionize the coldly injected $e_1hh_1$ excitons the accumulation of screening charges will be considerably suppressed and the ionization field is reached at small voltages. When, on the contrary, the trace is recorded in the reverse direction, i.e., starting from fields beyond the ionization threshold, the electric field is partly screened and, therefore, the photocurrent maximum occurs at higher gate voltages.

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[1] See, e.g., the special issues on *smart pixels* [IEEE J. Quantum Electron. **29**(2), 1993], *spatial light modulators* [Appl. Opt. **31**(20), 1992], and *optical computing* [Appl. Opt. **31**(26), 1992].
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