Photoluminescence modulation by high-frequency lateral electric fields in quantum wells

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(Received 5 December 2000; accepted for publication 19 January 2001)

We investigate the modulation of the excitonic photoluminescence (PL) of GaAs quantum wells by high-frequency (f_{rf}) lateral electric fields. Under these fields, the PL becomes modulated in the form of pulses with repetition frequency of $2f_{rf}$. The periodic PL modulation is attributed to the time-dependent ionization of photogenerated excitons under the lateral electric field. The exciton ionization mechanism is proposed to be the impact ionization with electrons accelerated by the electric fields with a threshold field for ionization of about 15 V/cm. The different transport properties of electrons and holes are found to play a role in the exciton ionization process. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1355292]

Quantum well structures driven by interdigitated metal gates are currently attracting much attention due to their interesting optoelectronic properties. Drexler *et al.*[1,2] reported strong lateral confinement and spin polarization in one-dimensional electron wires formed by applying a bias to metal stripes. Voltage-controlled exciton trapping and transport was investigated by Hagn *et al.*[3] and Zimmermann *et al.*[4,5] Schmeller *et al.*[6] reported the observation of the Franz–Keldysh effect in a two-dimensional system induced by a large lateral (i.e., parallel to the surface) electric field created by metal gates. Recently, Zimmermann *et al.*[7] and Zhang *et al.*[8] demonstrated the controlled storage and recombination of photogenerated carriers in these structures.

Many optoelectronic applications require a fast response of the electronic system to the electric field applied to the gates. In this contribution, we address this issue by investigating the modulation of the excitonic photoluminescence (PL) from quantum wells by a high-frequency (f_{rf}) lateral electric field. For that purpose, we performed spatially and time-resolved PL experiments on a single quantum well sample with interdigitated metal stripes shown in Fig. 1. Under an applied rf voltage, the PL intensity from QWs excited by a cw laser becomes a sequence of pulses with repetition frequency equal to the second harmonic ($2f_{rf}$) of fundamental rf frequency (f_{rf}). The modulation is attributed to the time-dependent ionization of excitons by the rf electric field. Since a successful exciton ionization requires the separation of electron-hole pairs by the alternating field, the transport properties of carriers were found to play a role in an effective ionization process. The exciton ionization under very low electric fields indicates that excitons ionize through lateral impact of field-accelerated electrons. An electric field threshold for impact ionization of 15 V/cm was determined from the dependence of the PL pulse width on the applied voltage.

The sample used in this study was an $Al_{0.3}Ga_{0.7}As$/GaAs/$Al_{0.3}Ga_{0.7}As$ single quantum-well structure with aluminum interdigitated gates illustrated in Fig. 1. The GaAs well is 15 nm thick and located 200 nm below the surface. The gate consists of 0.9 μm wide metal fingers separated by 0.9 μm. The sample was mounted in an optical cryostat with rf feedthroughs connected to a confocal microscope. The gate was driven by a high-frequency ac voltage $V_{rf}(t) = V_{rf,0}\sin(2\pi f_{rf}t)$ from a rf generator. The PL was excited by 765 nm cw laser focused down to a spot of about 2 μm on the sample surface. A fast photomultiplier (time resolution of 0.4 ns) synchronized with the rf generator was used to detect the PL from the excitation area. The voltage applied to the metal gates was determined by taking into account the rf reflection losses measured by a HP8753C network analyzer.

Spatially and time-resolved PL measurements were carried out at positions A and B in Fig. 1 at 14 K. The spatial distributions of the potential at these positions during positive and negative cycles of the rf voltage are shown schematically in this figure. At position A, there exists a potential dip between equipotential fingers, while at position B the potential varies almost linearly between fingers of opposite polarity.

The time-resolved PL traces measured at positions A and B for a rf voltage $V_{rf,0} = 11$ mV (for two different rf frequencies) are displayed in Figs. 2(a) and 2(b), respectively. The PL detected under the same conditions in a field-free situa-

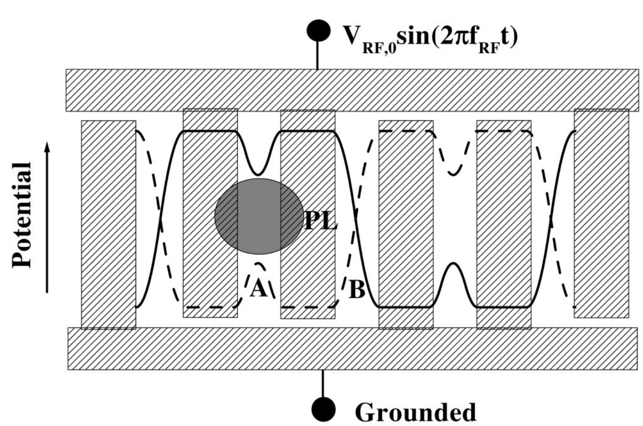

FIG. 1. Structure of the interdigitated metal gates and potential distributions in the quantum well under positive (solid line) and negative (dashed line) biases.

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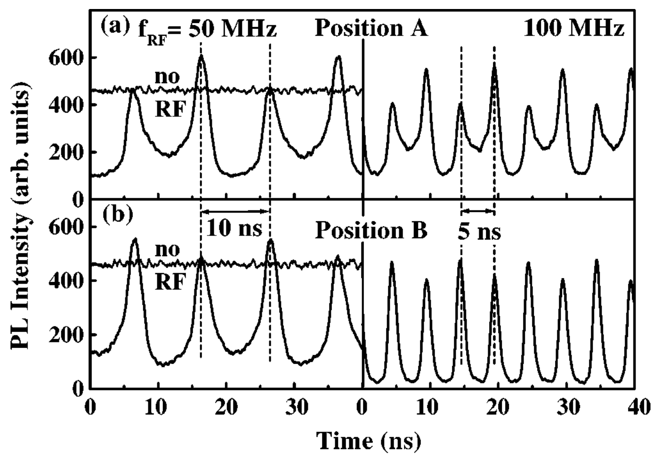

FIG. 2. Pulsed PL traces measured for $f_{rf}=50$ MHz (left) and $f_{rf}=100$ MHz (right) and for a rf voltage of 11 mV at (a) position A and (b) position B.

tion is indicated by the line labeled "no rf." The PL traces consist of pulses with repetition rates corresponding to the second harmonic ($2f_{rf}$) of the rf excitation frequencies.

The periodic modulation is attributed to the quenching of the PL signal induced by the lateral electric field produced by the metal gates. It can be understood based on the simple model presented in Fig. 3(a). When $V_{rf}(t)$ exceeds a threshold value corresponding to a threshold electric field E_t, the photogenerated excitons are ionized by the electric field, leading to a reduced PL response. In this case, PL pulses with a half width Δt appear twice within a rf cycle as shown in Fig. 3(b), in accordance with the experimental results. The free electrons and holes produced by exciton dissociation can be stored at positions A and B. As demonstrated in Ref. 8, these carriers recombine, when the rf field reverses its sign, leading to an additional contribution to the PL signal. The latter explains, why the intensity of the PL pulses may exceed the PL intensity in the absence of a rf voltage (see Fig. 2). Time-resolved PL traces recorded on the same sample after pulsed laser excitation (not shown here) show, in fact, a sequence of pulses delayed by multiples of $1/(2f_{rf})$, thus confirming the storage effect.[8] The integrated intensity of the delayed pulses, however, is less than one tenth of that of the first PL peak. For that reason, we will neglect the PL contribution from stored carriers in the discussion that follows.

To study the influence of the local potential profile on

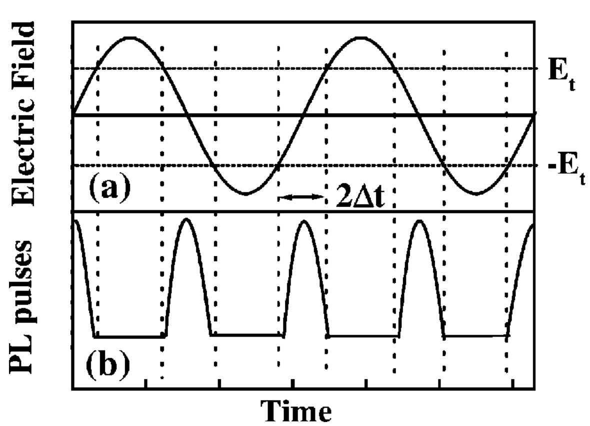

FIG. 3. Schematic time dependence of the electric field (a) and of the PL intensity (b).

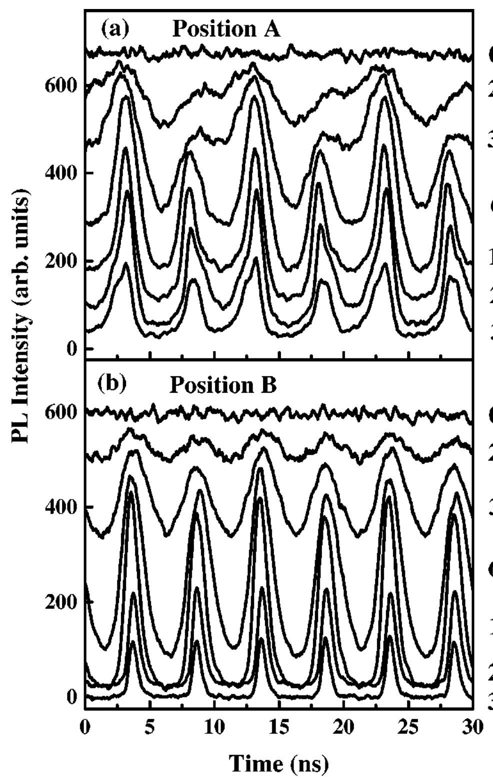

FIG. 4. PL traces measured under a rf excitation of 100 MHz for different rf voltages at (a) position A and (b) position B.

exciton ionization, PL traces were measured for $f_{rf}=100$ MHz and for different rf voltages at positions A and B, as shown in Figs. 4(a) and 4(b), respectively. At position B, the PL pulses have an almost uniform amplitude. At position A, however, every second pulse has a much lower amplitude. The effect, which becomes stronger at very low voltages, indicates that the PL in position A is not efficiently quenched in half of a rf cycle. We attribute this asymmetry to the difference in mobilities for electrons and holes. At position A, PL modulation requires the extraction of electrons (holes) produced by exciton dissociation from the potential dip (cf. Fig. 1) during the positive (negative) cycles of the rf voltage. Since the hole mobility in GaAs is much lower than that of electrons, holes will not be efficiently extracted during the negative rf half cycle, but recombine with electrons trapped in the dip. At position B, however, PL quenching only requires electron extraction, which can efficiently take place during both half cycles of the rf voltage. A modulation with uniform pulse amplitude is then always expected at this position.

The PL quenching at very low rf voltages indicates that optically generated excitons can be ionized by rather weak electric fields. According to the simple model shown in Fig. 3, the threshold electric field E_t for exciton ionization can be estimated from the rf voltage dependence of the width Δt of the PL pulses. If we approximate the electric field at position B by a constant V_{rf}/a and take into account the field reduction of $\exp(-2\pi d/a)\approx 25\%$[6] arising from the ratio between the depth $d=0.2\ \mu$m and the finger separation $a=0.9\ \mu$m, we obtain

$$E_t \approx \frac{V_{rf,0}}{a}\exp\left(-\frac{2\pi d}{a}\right)\sin(2\pi f \Delta t). \qquad (1)$$

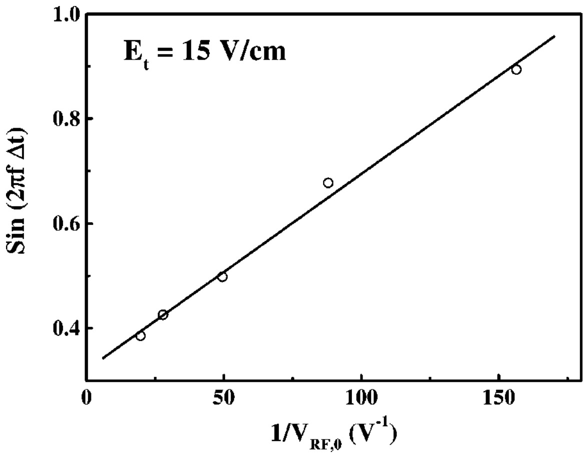

FIG. 5. $\sin(2\pi f\Delta t)$ vs $1/V_{rf,0}$ for position B. The data have been obtained from Fig. 4(b). The solid line is a linear fit to the data points.

Note this equation only applies when the electric field is much higher than the threshold value. In Fig. 5, $\sin(2\pi f\Delta t)$ is plotted as a function of $1/V_{rf,0}$. The slope of a linear fit to the data points results in a threshold field E_t of only 15 V/cm.

The threshold field is much lower than that required for direct ionization by field-induced tunneling, which is approximately given by the ratio $(E_{ex}/ea_B^*)\approx 10\,\mathrm{kV/cm}$ between the exciton binding energy ($E_{ex}\sim 10\,\mathrm{meV}$) and the effective Bohr radius ($a_B^*\sim 10\,\mathrm{nm}$). We conclude, therefore, that the latter mechanism cannot account for the strong quenching of the PL signal at high frequencies and low applied rf voltages. In fact, even under an applied field of 840 V/cm ($V_{rf,0}=300\,\mathrm{mV}$), we estimated a tunneling ionization time for free two-dimensional excitons[9] of 4.7 ns, which far exceeds the width of the PL pulses. We propose that excitonic ionization under these conditions takes place through impact ionization with electrons accelerated by the field, which is the dominant exciton ionization mechanism in bulk GaAs at low fields.[10]

In summary, high-frequency electric fields generated by interdigital metal gates can be used to control the PL response and the carrier dynamics in quantum wells. The PL intensity under cw excitation can be modulated in the form of PL pulses with the second harmonic of the field-modulation frequency. This structure shows potential applications for a field-controlled optoelectronic device.

The authors thank H. Grahn and Y. Takagaki for discussions and for a careful reading of the manuscript. Partial support from the Deutsche Forschungsgemeinschaft, DFG (Project No. SA598/2-1) is gratefully acknowledged.

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