Photocurrent-induced changes in the excitonic photoluminescence from a single heterojunction quantum well

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(Received 8 April 2008; revised manuscript received 13 August 2008; published 6 November 2008)

Excitons which coexist with a degenerate two-dimensional electron gas (2DEG) in the same quantum well subband have been observed in the photoluminescence (PL) from the recombination of electrons with localized photoexcited holes. Under pulsed photoexcitation at a critical applied voltage, the screening response of the 2DEG/exciton system to the appearance of a remote photocurrent filament in the 2DEG induces an increase in the integrated PL intensity, the formation of long-lifetime excitons in the excitation region, and long-lifetime redshifted PL from the excitation region and the region around the filament.

DOI: 10.1103/PhysRevB.78.193304 PACS number(s): 71.35.Lk, 72.40.+w

Research aimed at achieving the Bose-Einstein condensation (BEC) of excitons in semiconductor coupled quantum wells (CQWs) has stimulated strong interest in the long-range transport of nonequilibrium excitons[1] and photoexcited carriers in CQWs.[1–4] Long-distance in-plane diffusion of excitons has been observed in double quantum well structures.[5] Exciton transport out of the excitation region due to the exciton density and repulsive energy gradients[6] led to the observation of an inner PL ring around the excitation region.[1] Optical excitation above the barrier band-gap energy induces electron-hole separation and carrier transport which results in the observation of an external PL ring far from the excitation region.[1–4] There is significant disagreement in the observed speed at which photoexcited carriers diffuse out of the excitation region in semiconductor quantum well (QW)[7,8] and bulk[9,10] structures.

Excitons which coexist with a degenerate two-dimensional electron gas (2DEG) in the same subband have been observed in the photoluminescence (PL) spectra from the recombination of quasi-two-dimensional (2D) electrons with localized photoexcited holes in a single heterojunction quantum well (SHQW).[11] Over small ranges of applied gate voltage V_g and excitation intensity, we observed anomalous changes in the excitonic PL spectra which suggest that biexcitons have undergone a phase transition to an ordered collective phase.[11,12] In this Brief Report we report results which show that anomalous changes in the excitonic PL from the SHQW at or near a critical V_g are induced by the spontaneous appearance of a photocurrent filament in the 2DEG far from the photoexcitation region. Time-resolved (TR) PL measurements show that the screening response of the 2DEG/exciton system to the abrupt appearance of the remote photocurrent filament in the 2DEG induces an increase in the integrated PL intensity, the formation of long-lifetime excitons in the excitation region, and long-lifetime redshifted PL from the excitation region and the region around the filament.

Our experiments are carried out on a previously described AlGaAs/GaAs modulation-doped CQW,[11] which confines a 2DEG in the lowest subband of the SHQW formed by the transfer of electrons from the doped AlGaAs into the lower-band-gap GaAs. The 2DEG density was varied by applying a voltage V_g between a Schottky contact to the 120-μm-thick substrate and an Ohmic contact to the 2DEG. The samples were mounted in a variable-temperature liquid-helium cryostat, and excited with 50 ps, 3.8 MHz laser pulses with an excitation energy and intensity of 1.6 eV and 9 W/cm^2, respectively. The laser was focused to a spot size of 75 μm. The PL spectrum was measured using a 1 m imaging monochromator. Measurements of the TR PL spectra and the TR in-plane spatial profile of the PL were carried out at 2 K with a temporal and spatial resolution of 50 ps and 10 μm, respectively. Time-integrated PL spectra and time-averaged photocurrent-voltage (I-V) measurements were also carried out at 2 K.

The observed 2 K PL over the range of 1558–1544 meV is the superposition of the sharp, resonant PL from the recombination of spatially direct quasi-2D excitons and the relatively broad PL from the recombination of free electrons with localized heavy holes in the SHQW.[11] In the presence of a degenerate 2DEG, it has been predicted that the exciton characteristics will be sensitive to exclusion principle restrictions on electron scattering[13] as well as phase-space filling and exchange effects.[14] At $V_g=0$ V, the direct exciton emission results in a strong resonance in the observed 2 K time-integrated PL intensity at 1554 meV, as shown in Fig. 1. Previous results show that the 1554 meV PL resonance exhibits a diamagnetic shift in energy with the application of a magnetic field perpendicular to the SHQW, confirming that it is excitonic.[11]

Under illumination, photoexcited electrons generated by the absorption of photons in the undoped GaAs layer will drift into the SHQW due to the combined effects of the built-in electric field in our modulation-doped heterostructure and the applied V_g, resulting in a photocurrent. Figure 2 shows that we observe a sharp increase in the average photocurrent at the critical voltage $V_g=-36$ V and hysteresis in the I-V characteristics with subsequent variation in V_g, which is indicative of the formation of a photocurrent filament[15] from the undoped GaAs layer into the 2DEG in the SHQW.

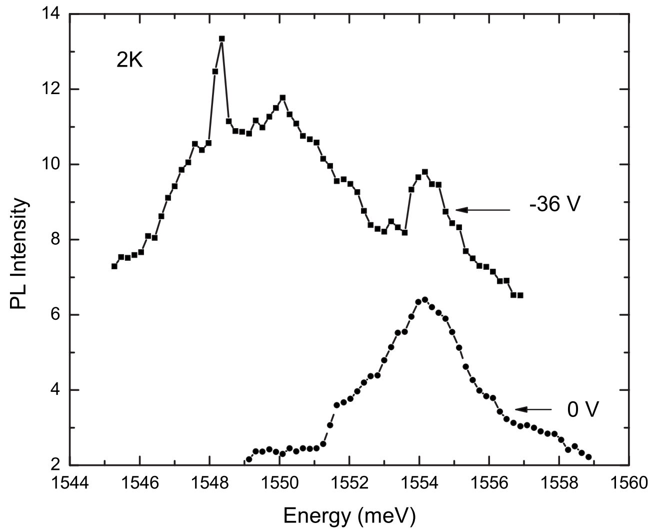

FIG. 1. Time-integrated 2 K PL spectra at $V_g=0$ V and $V_g=-36$ V.

The nucleation of a stable photocurrent filament in undoped GaAs occurs at a point where the local electric field (perpendicular to the SHQW) exceeds the threshold for charge-carrier multiplication due to impact ionization of shallow impurities.[15] Stability and heat dissipation considerations lead to a minimum current filament diameter.[15,16]

We observe concurrent, significant changes in the time-integrated excitonic PL at $V_g=-36$ V, as shown in Fig. 1. In addition to the 1554 meV exciton peak, we observe a broadened high-intensity PL peak at 1550 meV and a sharp peak at 1548 meV at $V_g=-36$ V. We are unsure of the origin of the sharp 1548 meV peak so we will not discuss it in the remainder of this paper. A comparison of the integrated PL intensity, obtained by integrating the time-integrated PL intensity over the energy range, shows that at $V_g=-36$ V there is a factor of 3.8 increase in the integrated PL intensity compared to that observed at $V_g=0$ V. This increase in the integrated PL intensity is primarily due to the appearance of the 1550 meV PL.

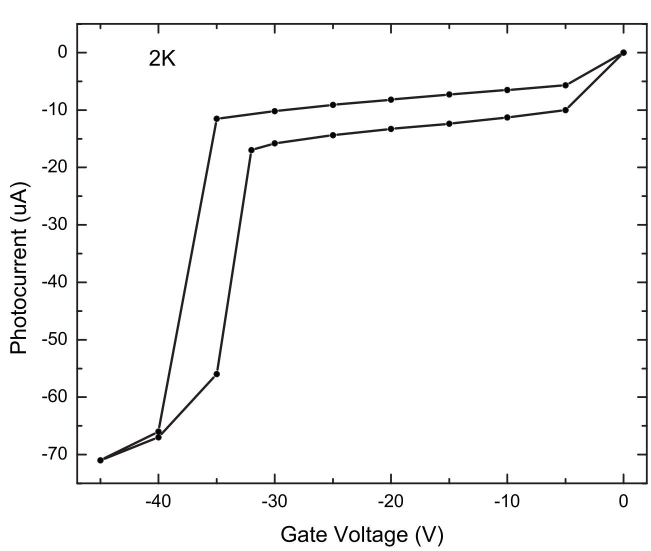

FIG. 2. Average 2 K photocurrent as a function of V_g.

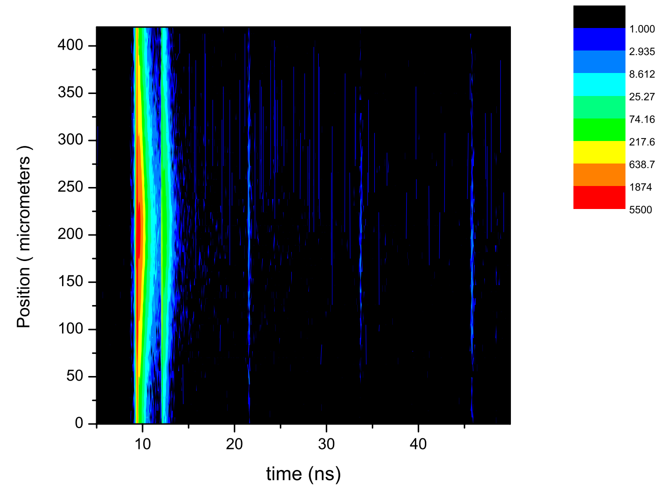

FIG. 3. (Color online) Time-resolved 2 K PL spatial profile at $V_g=0$ V. The PL intensity is color coded with the intensity scale shown in the inset. Excitation occurs at $t=9$ ns.

The time-resolved spatial PL profiles observed at $V_g=0$ V and $V_g=-36$ V are shown in Figs. 3 and 4, respectively. In these plots the PL intensity along an axis in the plane of the SHQW is plotted as a function of position and time after the laser pulse. The PL intensity is color coded with the intensity scale shown in these figures. Figure 3 shows that the PL profile at $V_g=0$ V is fairly symmetric about the center of the excitation region at $y \approx 190$ μm. Our laser excitation energy is lower than the 1.9 eV AlGaAs barrier band-gap energy and no PL rings are observed. The TR PL profile data, shown in Fig. 3, show that the 1554 meV exciton which is observed at $V_g=0$ V has a short lifetime with a PL intensity decay tail which extends out to around 3 ns after excitation. The relatively small increase in the 1554 meV PL intensity at around 3.2 ns is due to an unintentional, small laser pulse which occurs 3.2 ns after the main excitation laser pulse.

In striking contrast, the observed TR PL profile at $V_g=$

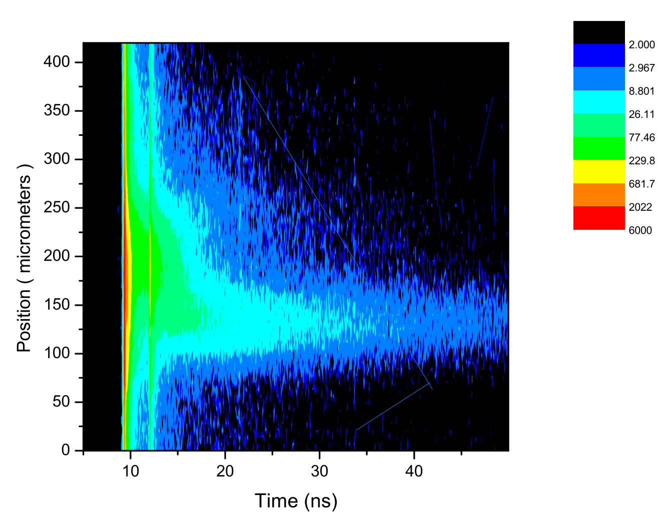

FIG. 4. (Color online) Time-resolved 2 K PL spatial profile at $V_g=-36$ V. The PL intensity is color coded with the intensity scale shown in the inset. Excitation occurs at $t=9$ ns.

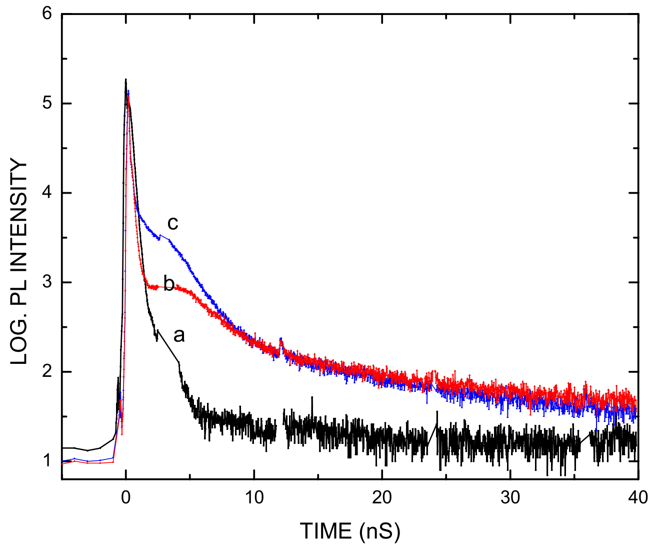

FIG. 5. (Color online) Logarithm of 2 K PL intensity as a function of time after laser pulse at: (a) 1554 meV with $V_g=0$ V, (b) 1554 meV with $V_g=-36$ V, and (c) 1550 meV with $V_g=-36$ V.

-36 V is asymmetric with respect to the center of the excitation region at $y\approx 190$ μm with a PL intensity decay tail which extends out to around 30 ns after excitation. For times greater than around 10 ns after excitation, the PL profile at $V_g=-36$ V is symmetric around the point $y\approx 130$ μm. The TR spatial PL profile in Fig. 4 shows that the PL observed at $V_g=-36$ V is the superposition of the PL from the photoexcitation region, which has the 10 ns decay tail, and the PL which has the 30 ns decay tail, and comes from the region that is centered at $y\approx 130$ μm. A comparison of the time-integrated PL intensity profile obtained by integrating the TR PL profile data shown in Fig. 4, with the time-integrated PL data for $V_g=-36$ V in Fig. 1, indicates that the 1550 meV PL comes from both the photoexcitation region and the region at $y\approx 130$ μm while the 1554 meV PL comes from the photoexcitation region. This data shows that the observed PL from the region at $y\approx 130$ μm is correlated with the formation of the photocurrent filament at $V_g=-36$ V. PL and TR PL data over the range -36 V$<V_g<0$ V are similar to that observed at $V_g=0$ V even though there is a small nonfilamentary photocurrent at these bias voltages. This confirms that the long-lifetime PL cannot be attributed to nonfilamentary carrier transport perpendicular to the SHQW. The PL data observed over the range -42 V$\leq V_g<-36$ V is similar to that observed at $V_g=-36$ V. Thermal effects lead to a decrease in the PL intensity for $V_g\leq -43$ V.

TR measurements of the PL intensity decay at the PL peak energies at $V_g=0$ V and $V_g=-36$ V were carried out and plotted in Fig. 5. TR measurements of the 2 K PL intensity at 1554 meV with $V_g=0$ V show that the PL exhibits an exponential decay over nearly three orders of magnitude of PL intensity with a lifetime of approximately 0.5 ns. At $V_g=-36$ V, both the 1554 and 1550 meV TR PL intensities exhibit an initially fast decay followed by a slow nonexponential decay tail which cannot be characterized by a single lifetime. At $V_g=-36$ V the 1554 and 1550 meV TR PL have a decay tail which extends out to about 10 ns. Figure 5 shows that over the 4–8 ns range the 1550 meV PL intensity is greater than the 1554 meV PL intensity. Figure 4 shows that the integrated PL over the 4–8 ns period from the region at $y\approx 130$ μm is greater than that from the photoexcitation region, confirming that the filament-induced PL from the region at $y\approx 130$ μm has only the 1550 meV component.

A consistent analysis of the data leads to the following qualitative model for our observations. Under pulsed photoexcitation at the critical voltage $V_g=-36$ V, a photocurrent filament flows into the 2DEG at the point $y\approx 130$ μm, 60 μm from the center of the photoexcitation region. This creates a filament-induced potential which is incompletely screened by the 2DEG[17] in the SHQW after roughly the dielectric relaxation time $\sim\epsilon/e\mu n\approx 10^{-15}$ s. It is important to point out that the dynamic many-body screening response of the 2DEG/exciton system in the photoexcitation region to the screened filament-induced potential must involve the excitons because of exclusion principle restrictions on electron scattering[13,14] and the resultant effects on exciton characteristics. The data shows that the photocurrent filament induces the formation of long-lifetime 1554 meV excitons and the rapid occurrence of 1550 meV PL, confirming that excitons in the photoexcitation region are involved in the screening response to the filament-induced potential. Our data also shows that the 2DEG/exciton response results in the observation of 1550 meV PL from the region around the filament. A substantial fraction of both the 1550 and 1554 meV PL exhibits relatively long lifetimes of around 5–8 ns.

The TR PL profile data in Fig. 3 and 4 show that, shortly after excitation at $V_g=-36$ V, the PL intensity at the filament position is approximately a factor of 8 larger than the PL intensity observed at the same point and time with $V_g=0$ V even though the laser excitation intensity at the filament position is unchanged. TR PL profile data in Fig. 4 shows that there is no observed delay between the PL peaks in the photoexcitation and the filament regions, indicating that there is no in-plane transport of excitons from the excitation region to the filament region. The observed anisotropic TR PL profile and the large increase in the integrated PL intensity at $V_g=-36$ V cannot be explained by successive photon emission and reabsorption. It has been predicted that collective exciton effects can induce a transition in the nonequilibrium exciton density in photoexcited semiconductors with an applied electric field.[18] The observed large increase in the integrated PL intensity at $V_g=-36$ V compared to that observed at $V_g=0$ V suggests that the 2DEG/exciton response to the photocurrent filament induces an increase in the nonequilibrium steady-state exciton density in the SHQW; however, further research is needed to understand the mechanism responsible for our observations. PL at localized spots in GaAs/AlGaAs CQWs has been observed before and attributed to recombination near sites with a large leakage current through the AlGaAs barrier.[4] The CQWs in these experiments did not have a quiescent 2DEG and the excitation energy was greater than the barrier band-gap energy. The SHQW structure is interesting for research on BEC since it has a high density of relatively long-lifetime excitons which undergo efficient electron-exciton scattering[19] near the ground state.

In conclusion, we have carried out time-resolved measurements of the PL spectra and the spatial profile of the PL from excitons which coexist with a 2DEG in a SHQW with an applied voltage. At the critical $V_g = -36$ V, the screening response of the 2DEG/exciton system to the appearance of a remote photocurrent filament in the 2DEG induces an increase in the integrated PL intensity, the formation of long-lifetime excitons in the excitation region, and long-lifetime redshifted PL from the excitation region and the region around the filament.

The authors thank D. Snoke for his invaluable support and advice, and M. Taysing-Lara for fabrication of the samples.

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