Field-effect persistent photoconductivity in AlAs and GaAs quantum wells with $Al_xGa_{1-x}As$ barriers

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We report a persistent increase or decrease in the two-dimensional electron density of AlAs or GaAs quantum wells flanked by $Al_xGa_{1-x}As$ barriers, brought about by illuminating the samples at $T\sim 4$ K, while simultaneously applying a voltage bias between a back gate and the two-dimensional electron gas. Control of the final carrier density is achieved by tuning the back gate bias *during* illumination. Furthermore, the strength of the persistent photoconductivity depends on the Al mole fraction in the back $Al_xGa_{1-x}As$ barrier, and is largest at $x\simeq 0.4$.

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Several compound semiconductors, when illuminated briefly at low temperatures ($T\lesssim 100$ K) with infrared or visible light, retain their photoconductivity for times that vary from a few minutes to hours or days. This remarkable phenomenon, called *persistent photoconductivity* (PPC), has been mostly observed in doped II–IV and III–V semiconductors such as AlGaAs:Si/Te,[1] ZnCdTe:Cl,[2] GaAsP:Te/S,[3] and AlN:Si,[4] in which it likely results from the formation of ''*DX*-centers.'' The latter are charged defect centers that behave as deep donors, and transform into metastable shallow donors under appropriate illumination. A successful microscopic model for the *DX*-centers in $Al_xGa_{1-x}As$, based on large lattice relaxation, has been established by Chadi and Chang.[5]

A general picture of PPC, however, is still conspicuously missing, and alternative models are still being invoked to explain its origin. Indeed, PPC also occurs in materials that do not contain *DX*-centers,[6–9] and can actually result in a *reduction* of the electrical conductivity, in which case it is referred to as *negative* PPC.[10,11] Aside from the *DX*-center model, another mechanism put forward to account for PPC involves the photoexcitation and subsequent separation of electron-hole pairs, followed by trapping of some of the electrons (or holes) by the spacers/barriers.[6,9] Deep levels in undoped materials such as GaN and GaAs may also result from the formation of anion antisites (e.g., N_{Ga}) or vacancies (V_{Ga} or V_{As} in GaAs).[7,8] In many cases, PPC probably stems from the cumulative effect of electron-hole pair excitation and relaxation of defects similar to the *DX*-centers.

The main result we wish to describe here, is that the two-dimensional (2D) carrier density (n) in a GaAs or AlAs quantum well (QW) with suitable $Al_xGa_{1-x}As$ barriers ($x\sim 0.4$), can be tuned reversibly from almost zero to values larger than 5×10^{11} cm^{-2}, by applying a small electric field (<500 V/cm) between the 2D electrons and a back gate, while briefly illuminating the sample at $T\simeq 4$ K with red light-emitting diode (LED) light. In other words, the zero-frequency dielectric permittivity of $Al_{0.39}Ga_{0.61}As$, which is equal to $12\epsilon_0$, increases effectively by two orders of magnitude when the material is illuminated at low temperatures, as calculated from the geometric capacitance of the sample. In samples with $Al_{0.39}Ga_{0.61}As$ barriers, the carrier density thus induced in the QW remains approximately constant after light is turned off, while with barriers with a lower Al content, the photoconductivity is only partly persistent. Though most of our measurements were done in AlAs QWs, we also have some limited data on GaAs QW's, which we will discuss later in this report.

To quantify this field-effect PPC (FEPPC), we have performed measurements in an 11-nm-wide AlAs QW grown by molecular-beam epitaxy (MBE), surrounded by $Al_{0.39}Ga_{0.61}As$ barriers, with a single Si front dopant layer separated from the QW by a 75-nm-thick $Al_{0.39}Ga_{0.61}As$ spacer (Fig. 1). Two samples were cut from the same wafer, one unpatterned and contacted in the van der Pauw geometry (sample *A*), and one patterned as a Hall-bar mesa (sample *B*). Both were fitted with a gate located on the back of the 400-μm-thick undoped GaAs substrate. 150-nm-thick AuGeNi contacts were deposited and alloyed at 440 °C, and samples were cooled in the dark, either in a ^{4}He dewar, or in a ^{3}He cryostat kept at $T\sim 4$ K. A red LED (wavelength 660 nm) was placed next to the sample at a distance of about 1 cm. The carrier density was determined through measurements of the Hall resistance R_{xy}. From transport measurements done on this and other samples, we have confirmed that the density deduced from R_{xy} at 4 K is the same as the 2D carrier density obtained from Shubnikov–de Haas data at 0.3 K. Magnetotransport data in AlAs samples illuminated using the technique described here have been reported elsewhere.[12]

Figure 2 illustrates the effect of illumination on the four-point resistance R of sample *A* with an applied back gate bias V_{BG}, at $T=4.2$ K. At time $t=0$, $V_{BG}=4$ V.[13] V_{BG} is first raised to 7 V, which changes R by a negligible amount in the dark. As the LED is turned on, R drops from 2400 to 830 Ω in about 30 s, after which it remains constant. The LED current is then turned off at $t=125$ s, which does not affect R. At $t=165$ s, V_{BG} is set back to 4 V, which does not change R in the dark, and then at $t=177$ s, the LED is turned back on. As a result, R now *increases* to reach a maximum of 2270 Ω, slightly lower than its value at $t=0$. After reaching this maximum, R slowly decreases while the LED is on. Finally, the LED is turned off again at $t=270$ s, keeping R unchanged. The data in Fig. 2 thus show that the resistance drop obtained after illumination at $V_{BG}=7$ V can be partly *reversed* by illuminating the sample at the ''original'' $V_{BG}=4$ V. The initial $R=2400$ Ω cannot be fully recovered at $V_{BG}=4$ V, however, indicating that the sample keeps some

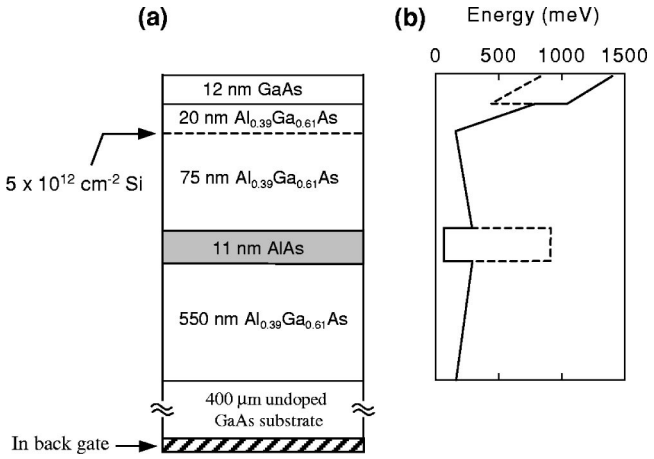

FIG. 1. (a) Layer structure of the AlAs QW. (b) Schematic conduction-band diagram of the sample. *X*-point and Γ-point conduction-band edges are indicated by solid and dashed lines, respectively.

memory of its illumination. This initial R can nevertheless be retrieved if the LED is turned on at V_{BG} *lower* than 4 V.

The evolution of R as we illuminate sample A at successively lower V_{BG}, is plotted in Fig. 3, obtained in a separate run. The current passing through the LED is plotted in the lower panel as a function of time. At time $t=0$, the sample density is low ($<2\times10^{11}$ cm^{-2}), and R is correspondingly high. At $t=15$ s, we illuminate the sample at $V_{BG}=30$ V until R drops to 260Ω and stops decreasing. We then reduce V_{BG} to 20 V, which does not affect R (even as we shine light upon the sample). We further decrease V_{BG} to 15 V, which in the dark does not change R either. The LED is then turned on: R increases, quickly reaches a maximum value of 530 Ω, then starts to decrease slowly, similarly to the behavior seen in Fig. 2. We turn off the LED right after R reaches its maximum value. (For our experiment at lower V_{BG}, this time is marked by a vertical arrow in Fig. 2.) R remains constant after illumination has stopped. This procedure is then repeated by (1) lowering V_{BG}, (2) illuminating the sample, thereby increasing R, and (3) turning the LED off as R comes close to its peak value. From the data of Fig. 3, we see that the resistance obtained after illumination increases as V_{BG} decreases. When light is applied at V_{BG} lower than 3 V, our contact resistance to the 2D electrons becomes too high for R to be measured reliably.

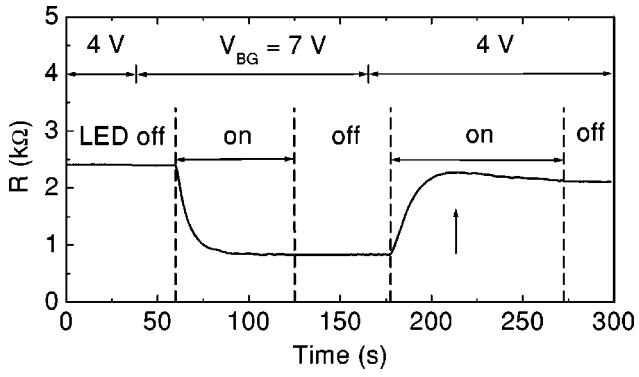

FIG. 2. Transient of the four-point resistance (R) of 2D electrons in an AlAs QW bordered by $Al_{0.39}Ga_{0.61}As$ barriers, as the sample is illuminated with a red LED, while a voltage bias (V_{BG}) is applied between the 2D electrons and a back gate (sample A). R first *decreases* as the LED is turned on at a higher V_{BG}, while the resistance *increases* when light is applied while V_{BG} is reset to its original value of 4 V. The peak value reached by R during this second illumination is about 5% lower that its value at $t=0$. R begins to decrease slowly after reaching its maximum, at a time marked by the vertical arrow.

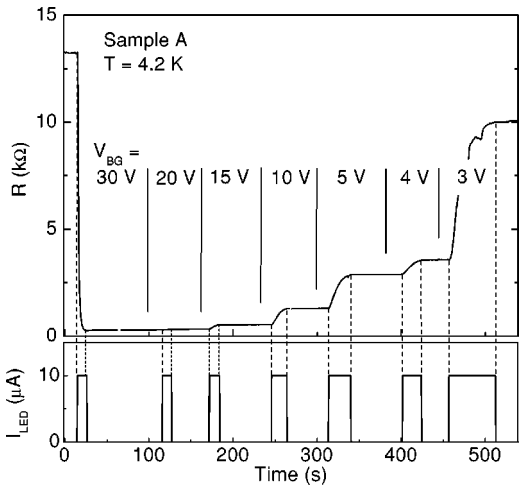

FIG. 3. Time dependence of the four-point resistance of 2D electrons in an AlAs QW, following the illumination sequence shown in the lower panel. Each illumination takes place at a different back gate bias, and is stopped when R reaches its maximum value (vertical arrow in Fig. 2).

A similar illumination sequence (with a denser set of back gate biases) was applied to sample B, and the carrier density was measured after every illumination. The density obtained after each exposure to light at V_{BG} is plotted as a function of V_{BG} in Fig. 4. For $V_{BG}>16$ V, the density remains constant at $n\simeq5.6\times10^{11}$ cm^{-2}, while for lower biases ($5<V_{BG}<14$ V), n decreases quickly and approximately linearly with V_{BG}. It is worth noting that the change in n with V_{BG} is

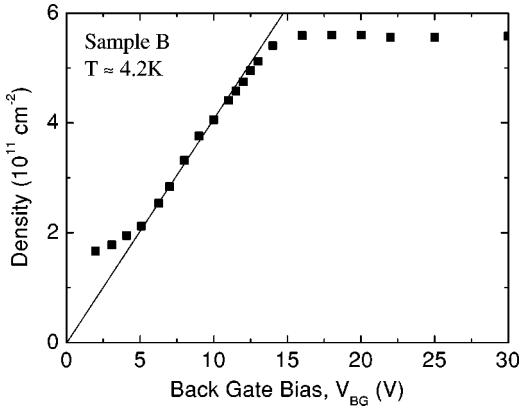

FIG. 4. 2D carrier density in an AlAs QW after illumination at gate bias V_{BG}, as a function of V_{BG}. Starting from a high density $n=5.6\times10^{11}$ cm^{-2}, n is lowered by illuminating the sample at gradually lower V_{BG}, as in Fig. 3.

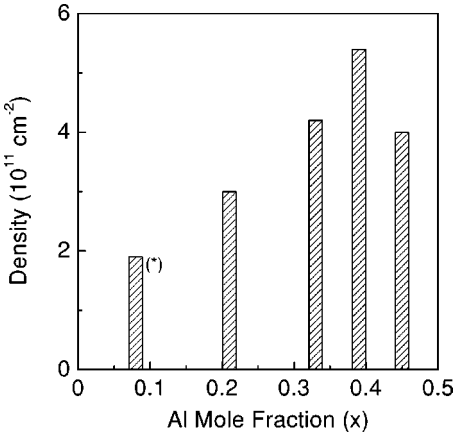

FIG. 5. Dependence of the electron density in an AlAs quantum well on the Al concentration (x_B) of back $Al_xGa_{1-x}As$ barriers. In each sample, a 2D electron gas is obtained after illumination at positive V_{BG}, as explained in the text. The bars indicate the range of 2D densities that can be obtained in the corresponding samples. The highest densities occur for $x_B \simeq 0.4$. Density data obtained for $x_B=0.4$ and $x_B=0.45$ were repeated in several wafers with nominally the same Al content in the back barrier: four wafers with $x_B=0.4$ and three different wafers with $x_B=0.45$. All sample structures are based on the layout shown in Fig. 1. (*) Because of the low Al content ($x_B=0.08$) of the back barrier in this sample, 2D electrons are located both in the AlAs QW and in the $Al_{0.08}Ga_{0.92}As$.

about 200 times larger than what it would be if this experiment were realized without illumination: in this case, the slope of $n(V_{BG})$ would be about 2×10^8 cm^{-2}/V.[14]

For $V_{BG} \lesssim 5$ V, the density decreases more slowly as V_{BG} is lowered. We note that for n lower than $\sim 1.7\times10^{11}$ cm^{-2}, our contact resistance in this sample becomes prohibitively high, preventing an accurate measurement of the density. As indicated earlier for sample A, we also note that the densities plotted in Fig. 4 depend on the history of conditions applied to the sample during a given cool down: a repeat of the sequence of illuminations at incremental values of V_{BG} tends to shift the curve of Fig. 4 to lower V_{BG}.

All of our other AlAs QW's with $Al_{0.39}Ga_{0.61}As$ barriers display a behavior qualitatively similar to that of Figs. 2–4: n can be tuned controllably from less than 2 to about 5×10^{11} cm^{-2}, by illuminating the sample at $0<V_{BG}<20$ V. In QW's confined within lower-x $Al_xGa_{1-x}As$ barriers, however, the maximum density obtained after illumination is lower than in samples with $x\simeq0.4$. We define this ''maximum'' density (n_{max}) in a given sample as that reached by increasing V_{BG} and by illuminating the sample at $T\sim4$ K for brief intervals (<5 s) until n saturates. The density obtained in this manner is characteristic of the sample, in the sense that it does not depend on cool down or on the history of illumination and gating.[15]

In Fig. 5, we plot n_{max} for different AlAs samples, as a function of the Al concentrations (x_B) in the back $Al_xGa_{1-x}As$ barrier. The structures grown above the AlAs QW in these samples, are all similar to the one shown in Fig. 1. As x_B decreases from 0.39 to 0.08, n_{max} decreases from about 5.6 to 1.9×10^{11} cm^{-2}, showing a direct correlation between x_B and sample density. Furthermore, out of the several samples grown with $x_B=0.45$, none has a density higher than 4.0×10^{11} cm^{-2}, indicating that the strongest FEPPC is obtained with $x_B\simeq0.4$. We point out that, when $x\gtrsim0.4$, the forbidden gap in $Al_xGa_{1-x}As$ becomes indirect, so that photons indeed are much less efficiently absorbed by the barriers.

Although we do not have a quantitative explanation for the phenomenon described in this report, we can nevertheless draw a qualitative picture of FEPPC from our measurements. First, since the effect depends sensitively on the Al concentration in the $Al_xGa_{1-x}As$ barrier *underneath* the QW, we suggest that the charged centers responsible for the increase in 2D carrier density after illumination are also located below the QW.[16] In addition, because of screening, the back gate has little effect on electric fields above the QW when 2D electrons are present in the QW. Thus, since the increase in 2D density brought about by illumination at $V_{BG}>15$ V is at least 4×10^{11} cm^{-2} (Fig. 4), we deduce that FEPPC creates $\gtrsim4\times10^{11}$ cm^{-2} positive charges *in the back* $Al_xGa_{1-x}As$ *barrier*.

Our next question concerns the nature of these positive charges in the back $Al_xGa_{1-x}As$ layer: Can they result from unintentional impurities present in the MBE during growth, or do they originate from some other kind of crystal defect? Because contaminants (mainly C) in our MBE are mostly incorporated as *acceptors* in the barriers, they cannot cause the effect we observe. Furthermore, the concentration of unintentional dopants required to produce a 2D density observed in our measurements needs to be greater than 5×10^{16} cm^{-3}, a value about 500 times greater than the estimated background impurity concentration in our samples. Thus residual impurities cannot explain the magnitude of the field- and light-induced electric charge, and we are led to conclude that this charge results from the presence of crystal defects in $Al_xGa_{1-x}As$, which are able to bind a positive charge at low temperatures. High quality $Al_xGa_{1-x}As$ alloys are notoriously difficult to grow by MBE, so a larger density of crystal defects is actually expected in this material.

A simple mechanism for FEPPC for $V_{BG}>0$, outlined below, can have two possible starting points: either photons absorbed by the back $Al_xGa_{1-x}As$ layer produce electron-hole pairs, which are then separated by the electric field; or light can induce a deep-to-shallow transition in levels associated with $Al_xGa_{1-x}As$ defects, thereby generating an effective (DX-like) donor in the barrier. In both scenarios, the field separates positive and negative charges spatially, attracting electrons towards the back gate, and repelling the positive charge towards the QW. Once the LED is turned off, some of the positive charges remain trapped in the $Al_xGa_{1-x}As$ close to the QW, creating an electric field that is much stronger than the field resulting from V_{BG}. We do not know at this point the nature and energetics of the charge-trapping defects, or the precise mechanism for charge transport through the $Al_xGa_{1-x}As$ during and after illumination. The reason why FEPPC is strongest for $x_B=0.4$ is also unknown, though it could be related to the near degeneracy of Γ and X conduction-band minima in $Al_{0.4}Ga_{0.6}As$.[17] Measurements of the photoluminescence and the photoconductiv-

ity spectrum, as well as optical deep level transient spectroscopy,[18] could yield valuable insight into the physics of FEPPC.

Our results in GaAs are qualitatively similar to those in AlAs: in GaAs QW's bounded by $Al_{0.39}Ga_{0.61}As$ barriers, we obtained a density increase of about 5×10^{11} cm^{-2} after illumination with $V_{BG}=6$ V (150 V/cm), while a much smaller density increase ($\sim1\times10^{11}$ cm^{-2}) was observed under illumination at $V_{BG}=0$ V. We did not measure the dependence of FEPPC on x_B in GaAs QW's.

Finally, we point out that when both front and back gates are added to the sample, densities as high as $n=9.6\times10^{11}$ cm^{-2} can be obtained after sample illumination. FEPPC may thus also occur in the top $Al_xGa_{1-x}As$ barrier, although the effect is complicated by the presence of intentional Si dopants near the surface of our sample. We have not studied the front-gate-dependent PPC in greater detail. It is also worth noting that when Si dopants are present in the *back* barrier of the sample, FEPPC seems to have a weaker effect on 2D carrier density, possibly because the dopant layer partly screens V_{BG} during illumination.

In summary, we describe in this paper the basic properties of a new form of persistent photoconductivity, tunable with an electric field. By illuminating AlAs or GaAs quantum wells (surrounded $Al_xGa_{1-x}As$ barriers), while applying an electric field ranging from 0 to ~500 V/cm across the back $Al_xGa_{1-x}As$ barrier, we can vary the 2D electron density from ~0 to more than 5×10^{11} cm^{-2}. FEPPC is strongly sensitive to the Al mole fraction of the back $Al_xGa_{1-x}As$ barrier: the light-induced 2D density increases with x, and reaches a maximum at $x\simeq0.4$. The fact that n depends chiefly on the Al content of the back barrier indicates that the charged centers responsible for back-gate-controlled FEPPC in our samples are mostly located within that barrier.

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[13] To obtain the initial state in this experiment, we illuminated the sample at $V_{BG}=4$ V.
[14] A small leakage current (I_{leak}) flows between 2D electrons and back gate when the LED is on. In our experiment, $I_{leak}\sim1.5$ nA at $V_{BG}=15$ V, which may thus lower the effective back gate bias applied to the sample, since I_{leak} causes a voltage drop through the semiinsulating GaAs substrate. Our setup does not allow measurement of the voltage potential drop across the $Al_xGa_{1-x}As$ barrier only.
[15] Densities up to twice higher than the nominal n_{max} in AlAs QW's with "low x" $Al_xGa_{1-x}As$ barriers ($x\lesssim0.3$), can be obtained by illuminating the sample for much longer times (minutes to tens of minutes).
[16] FEPPC is unlikely to be caused solely by a process within the AlAs QW, since the effect is also observed in GaAs QW's.
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