Optical reading of field-effect transistors by phase-space absorption quenching in a single InGaAs quantum well conducting channel

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We present the first observation of absorption quenching by electrical control of the carrier density in a single semiconductor quantum well used as conducting channel in a field-effect transistor. The effect is large enough to allow direct reading of the transistor logic state.

In this letter we present the first observation of absorption switching in a semiconductor quantum well by electrical control of the carrier density. We have observed this new effect at room temperature in a single modulation-doped InGaAs quantum well which was used as conducting channel of a field-effect transistor (FET). The physical mechanism that contributes the most to the absorption quenching is the filling of the phase space by the electrons as they are swept in the conducting quantum well channel. The effect is extremely large and we measure changes of absorption coefficient of $\Delta\alpha > 10^4$ cm^{-1} for a -0.6 V$\rightarrow +1.5$ V gate-source voltage modulation. We have used this phase-space absorption quenching (PAQ) for direct optical determination of the logic state of the FET.

Large changes in absorption in quantum wells have previously been successfully induced in quantum wells in this spectral region by photocarrier absorption bleaching[1] and the quantum confined Stark effect (QCSE).[2] In both of these it is difficult to extinguish the excitonic absorption completely. The QCSE is attractive for electrically driven optical modulators, although the usable spectral range is limited. In contrast, the absorption changes in the present PAQ effect appear to correspond to near complete quenching of the excitonic and above-band-gap absorption near the optical absorption edge, and this bleaching is observed over a ~ 90 meV spectral range.

This letter is organized as follows. First we present the principle of the PAQ and we discuss the physical processes it involves. Then we describe our samples and experiments. Finally we propose an interpretation and we conclude by commenting upon the potential applications of PAQ to direct optical reading of electric circuits using III-V semiconductor technology.

Undoped III-V semiconductor quantum wells (QW's) exhibit exciton enhanced absorption with exciton resonances clearly visible at room temperature.[1] Investigation of nonlinear optical effects in GaAs[1] and InGaAs[3] QW's has shown that photocarriers partly bleach the exciton resonances through effects of the exclusion principle.[4] On the other hand, carriers can be introduced permanently in QW's by modulation doping (MD).[5] This technique of doping spatially separates the impurities from the carrier thus producing very high mobility materials that have been extensively studied for their electronic transport properties.[6] MD has been applied in particular to the high-speed selectively doped heterostructure transistor (SDHT).[7]

The optical properties of MD QW's have been investigated less extensively. Because the carriers fill the two-dimensional (2D) subbands up to the Fermi energy E_F, it was found at low temperature in n-MD GaAs QW's that the absorption edge is blue shifted with respect to the luminescence emission.[8] This effect was used to avoid luminescence reabsorption in GaAs MD QW waveguides in the study of valence subband mixing.[9] This blue-shifting phenomenon is really an example of the Burstein–Moss shift long known in bulk semiconductors. More recently excitation spectroscopy investigations have revealed that electron-hole correlation singularities appear near E_F and that exciton resonances persist at the onset of the high-energy intersubband transitions ($n_z = 2$ and 3) even at large doping densities.[10] The persistence of these correlation effects has been theoretically explained by accounting for the weaker direct Coulomb screening in 2D.[11,12] The whole behavior including the excitonic correlation effects can be explained relatively completely by including phase-space filling (a generalization of Burstein–Moss shifting to include excitonic effects) and exchange. Phase-space filling is ultimately responsible for the quenching of absorption and means that the states normally available for absorption are not available because they are filled, while exchange and screening contributes to the band-gap renormalization effects that change the energies of the band gaps in the material.[11,12]

The above discussion clearly shows that electrically driven changes of the carrier density in a MD QW will result in large changes in optical absorption by modifying the phase-space filling. This is the essence of the PAQ. The conditions for its observation correspond exactly to the situation encountered during the switching of a SDHT containing a QW as the conducting channel.

The structure we have chosen to investigate is a recessed gate InGaAs/InAlAs SDHT grown on InP. This material system has a number of the advantages as compared to other III-V heterostructures such as GaAs/AlGaAs. The InGaAs channel material has a higher peak electron velocity than GaAs. The InAlAs layers and more importantly the InP substrate are transparent around the InGaAs gap. This can be exploited to probe the InGaAs QW through the substrate at an operating wavelength that is compatible with photonic devices for 1.5-μm lightwave communication systems. In the present experiment, we measure the changes in absorption in the channel, although we perform the experiment in reflec-

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tion by illuminating through the substrate from underneath the gate and reflecting off the gate metal, thus making two passes through the channel.

Variation of the reflectivity of a GaAs/AlGaAs SDHT through a transparent gate has been reported.[13] Changes in reflectivity varying between 0.1% and 0.3% have been observed at the various gaps and they have been interpreted as resulting from the Franz–Keldysh effect and from changes of the subband structure induced by the electric field.

The sample was grown by molecular beam epitaxy (MBE) and prepared using conventional photolithography and lift-off techniques.[14,15] Its structure is shown in Fig. 1(b). The epilayer structure consists first of a 3000-Å undoped $In_{0.52}Al_{0.48}As$ buffer layer, and an undoped $L_z = 100$-Å $In_{0.53}Ga_{0.47}As$ QW conducting channel for the 2D electron gas. The electrons are supplied by transfer through a 20-Å $In_{0.52}Al_{0.48}As$ spacer layer from the 250-Å $In_{0.52}Al_{0.48}As$ layer doped with Si $\sim 1.2\times10^{18}$ cm^{-3}. Finally an undoped 140-Å $In_{0.52}Al_{0.48}As$ and a 200-Å n^+-$In_{0.53}Ga_{0.47}As$ cap layer complete the structure. The epilayers are sequentially grown on a (100)-Fe doped InP substrate. Hall measurements indicate that the sample is of high quality. The low field mobilities are $\mu = 9432$ cm^2/V s at 300 K and $\mu = 36\,640$ cm^2/V s at 77 K. The corresponding sheet carrier densities are 1.79 and 1.6×10^{12} cm^{-2}. The ohmic contacts to source and drain regions are formed by alloying evaporated AuGe/Au in two steps at 400 and 430 °C. The Schottky gate pattern consists of two bonding pads connected to a 1.6 μm $\times$ 100 μm active region which is centered in a 5.4-μm gap between the source and the drain. The area of the epitaxial layer covered by this pattern was recessed 230 Å by slow chemical etch prior to deposition of the Schottky metal consisting of 300 Å Cr under 3000 Å Au. Finally the FET's are isolated by deep mesa etch. An air bridge was also formed during this step between the gate pad used for bonding and the active gate region. For the samples used in optical measurements the second gate pad 100 μm $\times$ 100 μm was left as contiguous part of the source-drain mesa to serve as active area for optical probing. All optical measurements reported here were made under this extended gate pad. The back side of the substrate was polished. Individual devices scribed from the processed wafer were mounted onto sapphire plates. After being mounted the devices were characterized at 300 K, examples of the source-drain current-voltage characteristics are shown in Fig. 1(a). No looping or hysteretic behavior was observed, and a peak transconductance of 116 mS/mm was measured.

For the optical measurements the output of a simple tungsten lamp/0.25 m monochromator setup was focused onto the active pad though the InP substrate and the light reflected from the Cr/Au electrode was detected by a PbS photodetector. Using conventional lock-in techniques, the change in the intensity of the reflected beam was measured as a function of the wavelength as the gate-source voltage was modulated. The signal ΔT is thus the change in transmission of the probe beam after two passes through the InGaAs quantum well conducting channel. In the small-signal regime we have $\Delta T \sim 2\times\Delta\alpha L_c$, where L_c is the channel thickness.

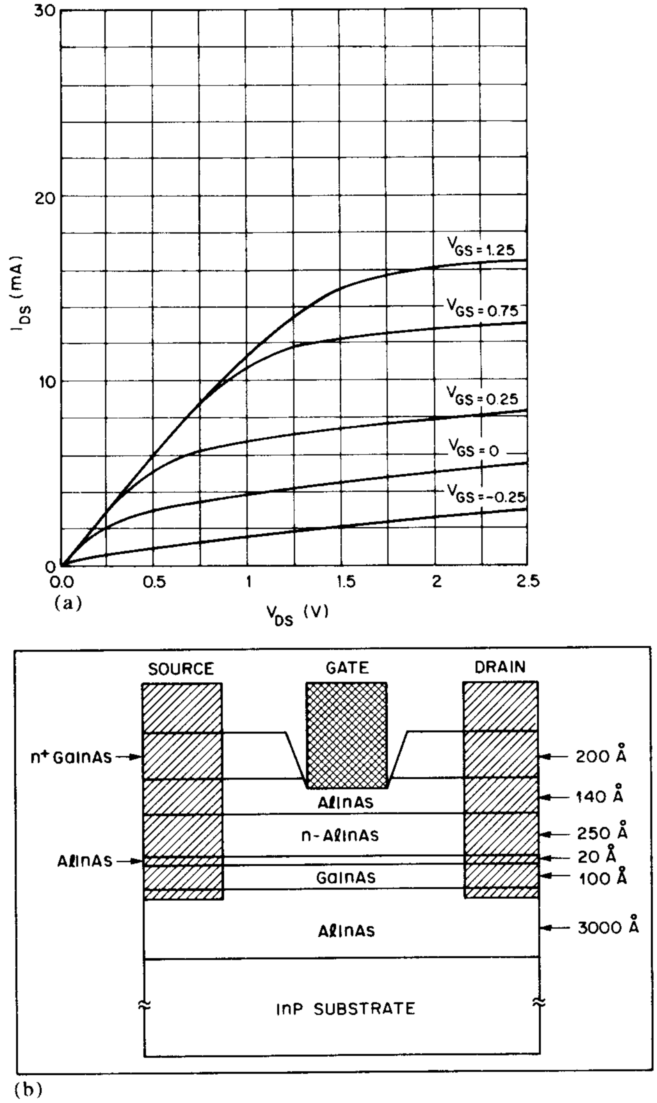

FIG. 1. Drain-source current/voltage characteristics of the InGaAs/InAlAs field-effect transistor used in our experiments. The FET structure is shown in (b).

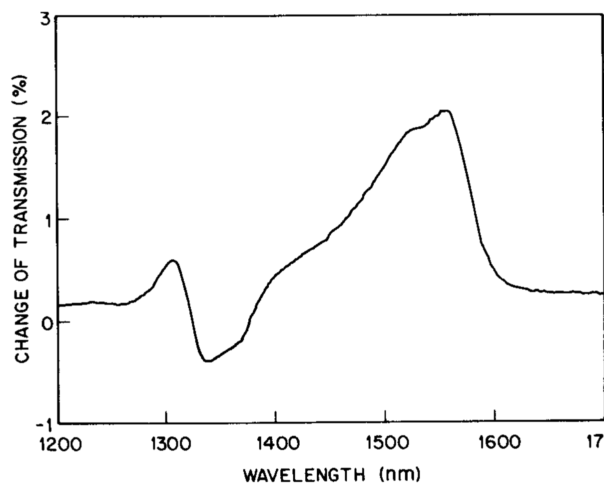

FIG. 2. Difference-absorption spectra showing the phase-space absorption quenching of the $n_z = 1$ exciton resonances ($\lambda \sim 1.55\,\mu$m) and the red shift of $n_z = 2$ resonance ($\lambda \sim 1.32\,\mu$m) as the 2D electron gas is expelled from the InGaAs quantum well conducting channel of the FET by the gate-source voltage.

A typical spectrum for a (− 0.5)-(+ 1.5 V) gate-source voltage modulation is shown in Fig. 2. In these data, the source-drain voltage is fixed at 0 V. A large change is clearly seen at the position of the $n_z = 1 (\lambda \sim 1.55\,\mu\text{m})$ exciton peaks with a maximum amplitude $\Delta T \sim 2\%$ and a somewhat weaker structure at the $n_z = 2$ resonance $(\lambda \sim 1.32\,\mu\text{m})$. The two features have very different spectral dependence. At the $n_z = 1$ excitons, the profile of the difference spectrum corresponds to a large bleaching of absorption without change of the position of the exciton resonances. Assuming that the entire area probed in the channel participates equally in the modulation and taking the channel thickness to be the quantum well thickness (i.e., $L_c = L_z$), we find $\Delta\alpha \sim 10^4\ \text{cm}^{-1}$ which corresponds to a total quenching of the excitonic absorption.[16] This interpretation is supported by the abruptness of the edge of the difference spectrum and the appearance of two features at the position of the heavy and light hole exciton peaks which both correspond quite well to the room-temperature absorption edge of undoped InGaAs QW's.[16] The variation of absorption at the $n_z = 2$ resonances has a completely different spectral profile which corresponds to a red shift of the $n_z = 2$ exciton peak.

We interpret these observations in the following manner. As the carrier density increases, the band-gap renormalization and the QCSE due to the field in the QW shift the band gap to lower energies.[10,11] At the $n_z = 1$ edge phase-space filling is effective in addition to the band-gap renormalization. In fact the absorption is quenched by the electron gas filling the states available for optical absorption, hence the name PAQ.[4,11] For our sheet concentration taking into account the recessing and using for the electron effective mass $m_e = 0.041 m_0$[17] we have $E_F \sim 93$ meV. The Fermi distribution, although spread because of the high temperature, covers an energy range of the order of E_F extended enough in the vicinity of the renormalized conduction subband edge to produce the PAQ seen in Fig. 1(a). At the absorption edge all the states are occupied and the excitonic absorption is totally quenched. For higher energies the occupation follows the thermal profile of the Fermi distribution; some states are available for absorption hence the "thermal" tail of the difference spectrum. At the $n_z = 2$ states the occupation is negligible and no quenching of absorption occurs. However, because of the band-gap renormalization and the QCSE, the $n_z = 2$ states experience a red shift and broadening, hence the "derivative" profile of the differential spectrum at these transmissions.

We have also measured similar changes of absorption with finite source-drain voltages, although the threshold voltages are changed. All the aforementioned observations are very reproducible from sample to sample. More detailed measurements and a more complete analysis will be published elsewhere.[18]

The potential for the application of PAQ in monitoring and optically interconnecting electronic circuits based on III-V semiconductor technology is clear. The effect is large enough to enable probing in a single QW and enables *direct observations* of the density of the conducting electron gas in the transistor. The modulation contrast could be improved by using several QW's, although there are limits to the number of heavily doped wells that can be depleted in this way. A more elegant way of increasing contrast that should give sufficient contrast to read the state of the transistor in real time at high speed is to propagate the light along the gate in an optical wave guiding structure, as has been successfully demonstrated in QCSE modulators containing only two quantum wells.[19] Such a device might also be an attractive device for communications applications.

In conclusion, we have identified a new optical modulation effect, the PAQ, which occurs as the charge density in the QW conducting channel of a SDHT is electrically varied. We have observed the effect at room temperature in a InGaAs/InAlAs grown on InP FET. The PAQ shows large absorption coefficient changes with relatively broad spectral bandwidth. We believe that this effect shows considerable potential for applications in monitoring electronic circuits, in optical interconnects, and as an optical modulator.

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