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Transport Properties of Epitaxial Lift Off Films

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ABSTRACT

Transport properties of epitaxially lifted-off (ELO) films were characterized using conductivity, Hall and Shubnikov-de Haas measurements. A 10-15% increase in the 2D electron gas concentration was observed in these films as compared with adjacent conventional samples. We believe this result to be caused by a backgating effect produced by a charge build up at the interface of the ELO film and the quartz substrate. This increase results in a substantial decrease in the quantum lifetime in the ELO samples, by 17-30%, but without a degradation in carrier mobility. Under persistent photoconductivity, only one subband was populated in the conventional structure, while in the ELO films the population of the second subband was clearly visible. However, the increase of the second subband concentration with increasing excitation is substantially smaller than anticipated due to screening of the backgating effect.

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I. Introduction

A significant effort is under way to integrate semiconductor
devices fabricated from material growth technologies that are
incompatible.   This is motivated by a desire to combine the
preferred device characteristics of different technologies and
materials to fabricate hybrid electronic circuits having superior
performance over that of conventional circuit configurations. An
important example of such an application is the integration of GaAs
based devices with Si technology.   By combining these two
technologies, one can take advantage of the superior frequency
response of GaAs based structures with the high device densities of
Si technology.

A common approach in integrating these two technologies has
been the epitaxial growth of GaAs on a Si host substrate [1].
There are, however, many inherent problems associated with the
epitaxial growth of GaAs on Si substrates due to the large lattice
mismatch of the two materials. This has resulted in only moderate
advances towards the integration of the two technologies.   An
alternative to this approach was proposed by Yablonovitch [2] and
consists of chemically removing the active GaAs based device layers
from their original growth substrate and mechanically attaching
them to the new host substrate, e.g. silicon. The epitaxial lift-
off (ELO) technique thus enables the integration by avoiding the
large number of material growth defects associated with the
epitaxial growth of lattice mismatched materials.

The integration of GaAs with Si is only one example where the
ELO process would be advantageous.   There are a variety of
materials with characteristics that are best suited for specific
device applications. For example, InP is an ideal material for
optical as well as fast low noise devices. Also high resistivity
substrates such as quartz and sapphire have lower dielectric
attenuation constants resulting in lower losses. The ELO process
could also be used in the integration of active semiconductor
devices with superconducting materials.

To date this technique has been successfully used to transfer

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solar cells [3], lasers [4] and field effect transistors (FET) [5] from their original growth substrates on to various host substrates without any degradation in performance. In our previous work, we presented rf measurements of peeled high electron mobility transistor (HEMT) structures [6]. The rf properties were shown to improve after the ELO process with an enhancement in the cut-off frequency, F_T, of 12-20% . A FET device has also been integrated into a microwave circuit to fabricate a 10 GHz narrow band amplifier [7].

Low-temperature photoluminescence studies of ELO films have indicated that the minority-carrier properties of the structures experience no degradation as a result of mechanically removing the epitaxial layers from the growth substrate [8]. The same reference also reports on the transport properties of the peeled films, showing identical values for the carrier mobility and concentration for a sample that has been peeled as compared with a sample that did not undergo the ELO process. The measurements were carried out at 300 and 77 K.

In this paper we report on the 2D electron gas (2DEG) transport properties of peeled HEMT structures as determined by conductivity, Hall and Shubnikov-de Haas (SdH) effect techniques at temperatures down to 1.4 K. The Hall effect gives a value for the total concentration which may include parallel conducting paths outside of the quantum well region. The SdH technique on the other hand, gives a true value of the 2D concentration based on the frequency of oscillation of the SdH waveform. From the SdH technique we can also derive such properties as the quantum scattering time and the effective mass. In this paper we present an in depth comparison between the physical properties of peeled HEMT structures attached to a quartz substrate and identical structures on adjacent samples still attached to the original GaAs growth substrate.

II. Sample Preparation

A cross sectional view of the three structures used in this study is shown in Figure 1. Three different structures were chosen in order to be able to ascertain the effects of the ELO process on the transport characteristics. Structure 1 consisted of a GaAs channel with an $Al_{.30}Ga_{.70}As$ barrier layer that was homogeneously doped with Si to a nominal value of $1.0x10^{18}$ /cm^3. Structure 2 varied from structure 1 only in that the barrier was Si delta-doped to a nominal value of $3.5x10^{12}/cm^2$. Structure 3 was an $Al_{.23}Ga_{.77}As/In_{.20}Ga_{.80}As$ pseudomorphic structure delta-doped in the AlGaAs barrier also to a nominal value $3.5x10^{12}/cm^2$. A 500 Å AlAs release layer was grown between the substrate and the active device layers for all the structures in order to carry out the ELO process. Hall bars were fabricated using a standard mesa process with contacts consisting of Au/Ge/Au/Ni/Au. All of the device fabrication was carried out prior to the lift-off process.

Peeling of the devices was carried out by selectively etching the AlAs release layer using an HF:DI solution. The HF etches the AlAs layer at a rate of approximately 10^7 faster than that of the GaAs layer. This is true also for AlGaAs layers with an Al concentration higher than 50% [2]. The structures were coated with a thin layer of Apiezon wax which provides a compressive force to aid in the etching of the AlAs layer. The wax also serves as a mechanical support for the peeled layers after they have been removed from their growth substrate. Lift-off of the active layers generally takes approximately 12 hrs after it is placed in the HF solution.

After the active device layer is removed from its growth sub-strate, it is attached to a new host substrate via Van der Walls forces. In this study the ELO structures were attached to a quartz substrate, which is an insulator compared to the original seminsulating GaAs substrate. The Apiezon wax was then removed using trichloroethylene exposing the pads for bonding. Once the pads were bonded, they were mechanically reinforced using a silver

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paint cement.

III. Experimental/Results

The transport properties of ELO films of several HEMT structures were compared with identical samples still attached to their original GaAs growth substrate, labeled in this paper as "conventional" samples. The ELO films were from adjacent locations on the same wafer as the conventional samples. The transport parameters were derived from measurements of conductivity, Hall and SdH effects. Figure 2a shows the Hall concentration, n_H, as a function of temperature for the ELO and conventional samples. We see from the figure that there is very little difference in the value for the Hall carrier concentration for the ELO and conventional samples for all three structures. The slight increase in the concentration of the ELO sample observed for structure 3 is within experimental error. Very similar results were obtained for the measured Hall mobilities as shown in Figure 2b. For each of the three structures, there was no observable degradation of the mobility as a result of the ELO process.

While a value for the total carrier concentration is obtained from the Hall voltage, the frequency of oscillation of the SdH waveform gives the 2DEG electron concentration of the various subbands. The 2DEG concentration derived from the SdH data is considered very accurate, with errors of only up to 1% . Table 1 summarizes the values derived from the analysis of the data obtained from the Hall and SdH effects measured at 4.2 K under dark conditions where only single subband population was detected. We see that there was a consistent increase in the SdH 2D carrier concentration for all of the ELO samples with respect to the conventional samples. This increase in concentration was between 10 and 15% .

Values for the carrier concentrations and mobilities for the various samples were also obtained by simultaneously fitting the conductance and Hall voltages as a function of magnetic field. The

details of the calculation will be described in another paper [9]. By fitting these two sets of data we were able to derive values for the mobility and concentration not only of the 2DEG but also for the carriers in the parallel conducting path; in this case, the AlGaAs layer. Figures 3a and 3b show the estimated carrier concentration and mobility derived from this process for the ELO and conventional samples of structure 2 for a temperature range of 50K to 300K. There was very little difference between the mobility of the carriers in the ELO and conventional samples. The fitted value of the carrier concentration of the 2DEG showed the same increase for the ELO sample over the conventional sample as observed through the SdH oscillations.

Using illumination as a way to the generate excess carriers in the structures, we were able to determine changes in the quantum states that occur as a result of the ELO process. The carriers are generated as a result of a persistent photo-conductivity (PPC) effect present in the samples. Illumination of the samples was done for short periods of time to increase the concentration gradually. The ELO and conventional samples were placed simultaneously inside the cryostat thus applying an equal amount of excitation to each sample. After each illumination period, the cryostat window was covered and measurements of the Hall and oscillatory magneto-resistance were recorded. The excitation of carriers was carried out to the point of saturation where no new carriers could be generated by illumination. In this manner it was possible to observe the increase in population of the various subbands as well as to determine the dependence of the mobility on carrier concentration.

Figures 4a and 4b show the SdH waveforms for ELO and conventional samples of structure 2 respectively, after having been illuminated for the same amount of time. The insert is the fast Fourier transform (FFT) of the oscillations of the SdH waveform. The frequency (in 1/B, where B is the magnetic field) renders the electron concentration in the subbands of the 2DEG. The waveform for the ELO sample showed a clear superposition of a high and low

frequency associated with the first and second subbands. The FFT for this waveform consisted of two well defined peaks that correspond to the first and second subbands. This is in contrast to the conventional sample where no superposition is observed, i.e. the population of the second subband is below $3 \cdot 10^{10}$ cm^{-2}. Only a single peak, corresponding to the ground subband, was evident in all of its FFTs. The gradual increase of the subband concentrations, n_1 and n_2, as a function of illumination in arbitrary units, for the same ELO and conventional samples of structure 2, are shown in Figure 5. Whereas population of a second subband occurred after only a short period of illumination for the ELO sample, it was seen that even at the largest concentration, where saturation occurs, no population of the second subband was detected for the conventional sample. The two samples however, experienced the same drop in mobility (approximately half of its original value) after illumination. A more gradual decrease in mobility was observed in structure 3, as seen in Figure 6, in which substantial PPC was attained in spite of the low aluminum content [10]. Similar to structure 2, the mobility of both the ELO and conventional samples began to drop by the same amount as the Hall concentration was increased beyond a certain point.

Finally, using the 2D theoretical expression for the SdH conductivity amplitude, we were able to obtain a value for the quantum relaxation time (τ_q) as well as a value for the effective mass (m^*) of the carriers inside the quantum well. The expression is only valid for single subband population. The expression is shown in equation 1, where T is the electron temperature, E_F is the Fermi energy and ω_c is the cyclotron resonance frequency, $\omega_c = eB/m^*$.

$$\rho_{xx}(OSC) = \frac{C(\omega_c\tau_q)^2}{1+(\omega_c\tau_q)^2}\left[\frac{x}{\sinh(x)}\right]\exp\left[\frac{-\pi}{\omega_c\tau_q}\right]\cos(\frac{2\pi E_F}{\hbar\omega_c})$$

$$\text{where } X = \frac{2\pi^2 kT}{\hbar w_c}$$

Eq. 1

The quantum relaxation time was obtained from a least-squares fit of the amplitude of the various peaks at constant T with τ_q as the single adjustable parameter in eq.1 . The effective mass on the other hand, was obtained from a least-squares fit of the temperature dependence of the amplitudes of a particular peak, i.e. at a constant magnetic field value, using m^* as the adjustable parameter. In table 1 we see that the quantum scattering time was smaller for the ELO samples compared with the conventional samples for each of the different structures. From the analysis we also found that the effective mass of the carriers was the same for the ELO and conventional samples. The values for τ_q and m^* were derived for samples under dark conditions where only single subband population was detected.

IV.   DISCUSSION

By applying a bias to a gate on the back side of a heterojunction it is possible to increase its 2DEG concentration by raising its Fermi level.   If the concentration is increased sufficiently, this modulation may lead to a shift from single subband population to two subband population in the quantum well. Stormer et al. [11] were able to increase the 2DEG concentration from $7.5\cdot10^{11}$ cm^{-2} to $9.5\cdot10^{11}$ cm^{-2} by applying a back bias.

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The population of the second subband, as carrier concentration is increased, was an issue for debate. When PPC was used to increase the concentration, it was observed that the population of both subbands increase at a similar rate [12]. This is due to the similar density of states [13]. On the other hand, when the electron concentration was increased by a backgate voltage, the population of the second subband increased, while that of the lowest subband remained constant [11]. Vinter [14] showed that this discrepancy is due to the different processes leading to the increase in population. Using a gate, the increase of the potential lowers the energy of the second subband, i.e. E_2 is closer to E_1, thus increasing the population of that subband only.

Our measurements show a unique feature in which both subband concentrations increased under illumination, but that of the second subband increased much less than that of the first. The larger 2DEG concentration and the different distribution of the carriers between the two subbands in the ELO samples that we observed, can be explained by a combination of a backgating effect with PPC. The backgating is probably produced by a charge build up at the interface of the host substrate and the ELO film. The generated potential renders a larger dark concentration for the ELO samples. Additional carriers are injected by illumination. This process continues until the Fermi level reaches the barrier energy. Any additional flux generates carriers at the barrier while the 2DEG concentration saturates. Our measurements indicate that this point is reached at a stage when the Fermi level barely reaches the second subband in the conventional samples. Therefore in these samples no significant carrier population of the second subband is apparent in Figure 5. On the other hand the presence of a backgate potential in the ELO samples lowers the energy level of this subband below the barrier. Thus a detectable carrier concentration is present, as indicated by the superposition and the second peak in the FFT of Figure 5. This is according to the results by Vinter [14] who indicated that the spacing between the energy bands

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decreases as a result of backgating. Our self-consistent calculations of the energy states show that when a potential is acting on the active layers, the spacing between the ground subband and the first excited subband are reduced by approximately 10 meV.

The third issue is the minimal growth of the second subband population with increased illumination. In our case there is a constant gate charge. The increased 2DEG concentration has the effect of screening this gate charge, which leads to an increase of the spacing between E_2 and E_1. Thus the additional charge generated by the PPC resides mostly in the ground subband, proportionally much more than the case when no gate charge is present.

Further insight into the quantum states and scattering parameters is obtained from the carrier mobility versus concentration curve shown in Figure 6 for structure 3. We see that there was an initial increase in the mobility as the concentration increased. This comes about as a result of a screening of the scattering centers by the added carriers. Following the initial increase, there was a sharp peak in the mobility after which it began to decrease rather abruptly. This sharp peak corresponded to a carrier concentration where inter-subband scattering became more prominent. The added inter-subband scattering causes a drop in the carrier mobility at the onset of second subband population [11,15]. The effects of inter-subband scattering were present even though we were unable to detect second subband population in the quantum well as the mobility versus concentration results indicate. Therefore, even though the energy separation of the ground subband and the second subband was smaller for the ELO sample, we observed that the effects of intersubband scattering were comparable for both samples. This was also the case for structure 2 where it was seen that the carrier mobility dropped by half of its original value for both the ELO and conventional samples after illumination. The mobilities were the same even though second subband population was detected only in the ELO sample.

In Figure 6 there appears to be a slight shift in the mobility

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peak as a function of Hall concentration for the ELO sample. This shift in the curve is misleading however when you consider that the Hall concentration is a value for the total concentration and includes effects due to parallel conducting paths. A true value for the 2D carrier concentration is obtained from SdH analysis. We find that both peaks in the carrier mobility curve correspond to the same 2D concentration of $1.7 \times 10^{12}/cm^2$.

The effective mass of the carriers, derived from the temperature dependence of the SdH peaks, also remained the same after ELO. Using the well known relation, $u = q\tau_s/m^*$, we find that the transport scattering time, τ_s, is not affected by ELO since both the carrier mobility and effective mass do not change after lift-off. Typical values of τ_s were of the order of a few pico-seconds at the lower temperatures for all of the structures tested. Thus we see that large angle scattering, which contributes the most to τ_s, is not enhanced by the transfer of the active device layers on to the quartz substrate.

We see from table 1, however, that the same was not true of the quantum scattering time, τ_q, were a drop of between 17-36% was observed for the ELO samples compared to the conventional samples. This drop in τ_q most probably comes about as a result of the increase in the 2D concentration in the ELO sample and can be explained by the theoretical analysis of Isihara and Smrcka [16]. At low concentrations, τ_q increases steeply as a function of concentration as the energy of the electrons increases and becomes larger than the localization energy at the bottom of the conduction band. The curve reaches a maximum and begins to drop as the Fermi level increases and forces the electrons to the surface where they come into closer contact with the scattering impurities. This results in an enhancement of the small angle scattering effects and leads to the observed decrease in τ_q for the ELO samples.

For the homogeneously doped structure 1, the 17% drop in τ_q for the ELO sample was considerably lower compared with the approximate 36% drop of the much higher doped structures 2 and 3.

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This occurs even though there is the same 10-15% increase in the 2D concentration of the ELO sample as with the other structures. This would seem to indicate that the doping concentration of structure 1 corresponds to a point close to the maximum of the τ_q as a function of concentration curve. At this point in the curve, close to the maximum, the slope is small compared to the larger concentrations were τ_q changes very quickly. It should be noted that the drop in τ_q was also evident in the pseudomorphic structure. Therefore the drop in τ_q is a property of the ELO process and not a characteristic of the material. The drop in τ_q occurs as a result of the increase in the 2D concentration and not due to changes in the strained layer.

CONCLUSION

A comparison of the ELO and conventional samples by SdH analysis indicates several significant differences that are not apparent from standard Hall measurements. While the measured Hall concentration was the same for the ELO and conventional samples, the 2D concentration derived from the SdH waveform, was consistently 10-15% higher for the ELO samples. The quantum scattering times were also 17-36% lower for the ELO samples. This is in marked contrast to the transport scattering time, derived from the mobility and effective mass, which was identical within each pair. Also under PPC single subband population was observed in the conventional structures while two subbands were populated in the ELO films. We believe that the differences are due to a charging of the ELO film which acts as a backgate. It would be instructive to implement an electrode on this surface to investigate the effects of controlled backgating on these parameters.

Acknowledgments

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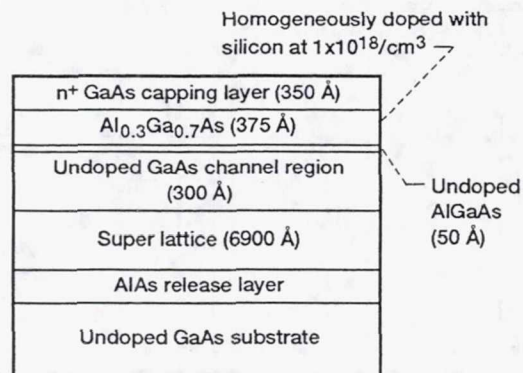
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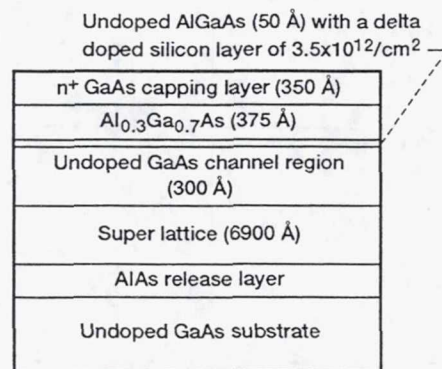   Phys. C.: Solid State Phys., vol. 19, 1986, pp. 6777-6789.

TABLE 1: HALL AND SdH DATA MEASURED AT 4.2K for ELO AND CONVENTIONAL SAMPLES WITH ZERO ILLUMINATION.

	STRUCTURE 1		STRUCTURE 2		STRUCTURE 3	
	ELO	CONV.	ELO	CONV.	ELO	CONV.
$\mu_H \left(x\ 10^4 \dfrac{cm^2}{V.sec} \right)$	10.7	10.5	8.18	8.01	4.43	4.47
$n_H \left(x\ 10^{12} \dfrac{1}{cm^2} \right)$	.709	.645	1.17	1.09	1.79	1.72
$n_{2D} \left(x\ 10^{12} \dfrac{1}{cm^2} \right)$	.549	.476	1.03	.936	1.65	1.5
$\tau_q \left(\dfrac{1}{psec} \right)$	.49	.59	.26	.4	.34	.53
m^*					$.067m_0$	$.067m_0$

Homogeneously doped with
silicon at $1\times10^{18}/cm^3$ →

| n+ GaAs capping layer (350 Å) |
| Al$_{0.3}$Ga$_{0.7}$As (375 Å) |
| Undoped GaAs channel region (300 Å) |
| Super lattice (6900 Å) |
| AlAs release layer |
| Undoped GaAs substrate |

— Undoped
AlGaAs
(50 Å)

(a) Structure 1 - GaAs channel with homogeneously
doped Al$_{0.3}$Ga$_{0.7}$As barrier.

Undoped AlGaAs (50 Å) with a delta
doped silicon layer of $3.5\times10^{12}/cm^2$ →

| n+ GaAs capping layer (350 Å) |
| Al$_{0.3}$Ga$_{0.7}$As (375 Å) |
| Undoped GaAs channel region (300 Å) |
| Super lattice (6900 Å) |
| AlAs release layer |
| Undoped GaAs substrate |

(b) Structure 2 - GaAs channel with delta-doped
Al$_{0.3}$Ga$_{0.7}$As barrier.

Undoped AlGaAs (50 Å) with a delta
doped silicon layer of $3.5\times10^{12}/cm^2$ →

| n+ GaAs capping layer (350 Å) |
| Al$_{0.23}$Ga$_{0.77}$As (375 Å) |
| Undoped In$_{0.2}$Ga$_{0.8}$As channel region (150 Å) |
| GaAs layer and super lattice |
| AlAs release layer |
| Undoped GaAs substrate |

(c) Structure 3 - In$_{0.2}$Ga$_{0.8}$As channel with delta-
doped Al$_{0.23}$Ga$_{0.77}$As barrier.

Figure 1.—Cross sectional views.

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(a) Carrier concentration.

(b) Carrier mobility as a function of temperature for ELO and conventional samples of Structures 1, 2 and 3.

Figure 2.—Measured Hall data.

(a) Carrier concentration.

(b) Carrier mobility.
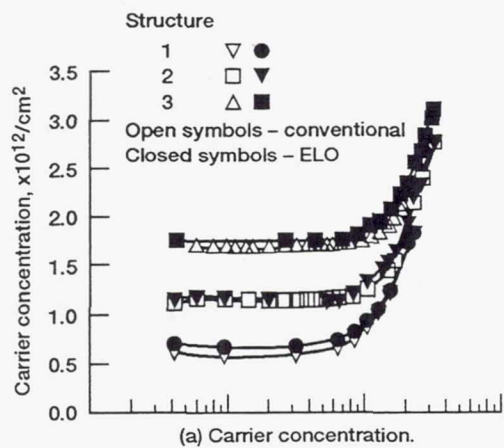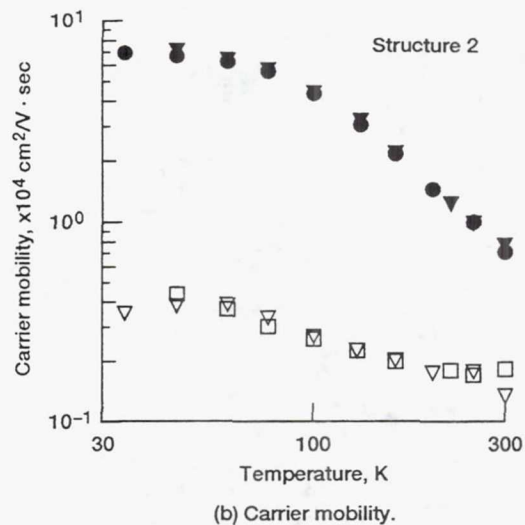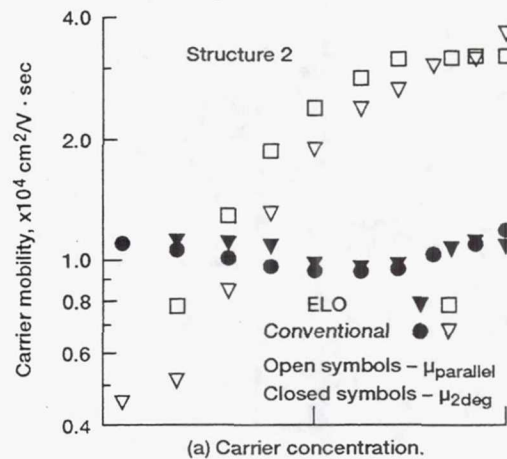
Figure 3.—Derived from fitting procedure as a function of temperature for ELO and conventional samples of Structure 2.

(a) ELO.

(b) Conventional.
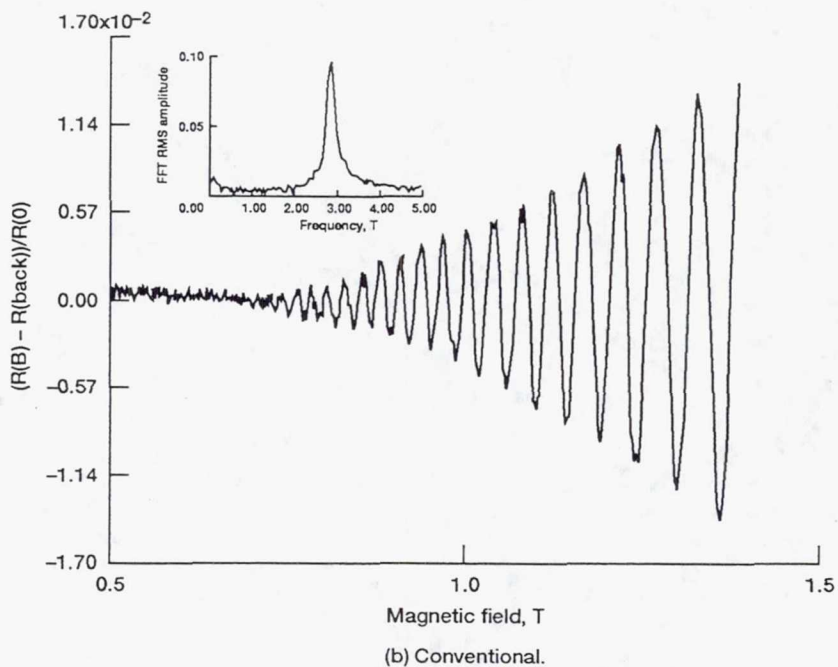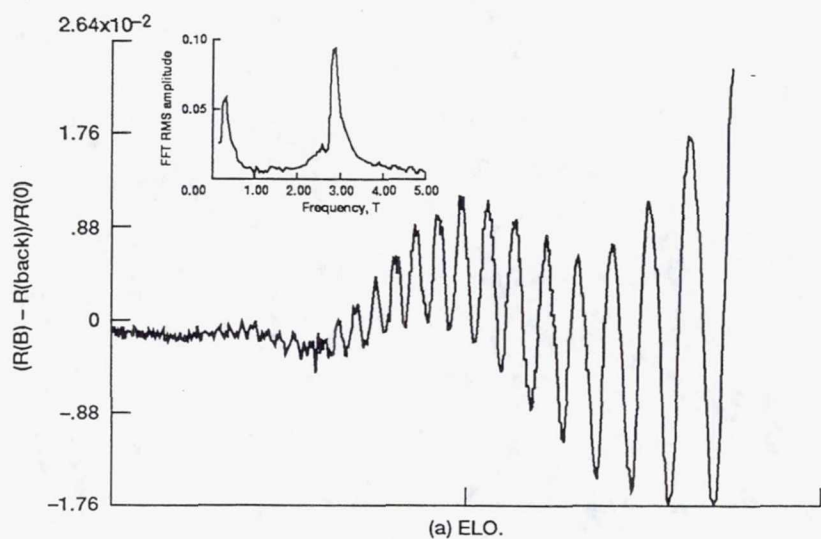
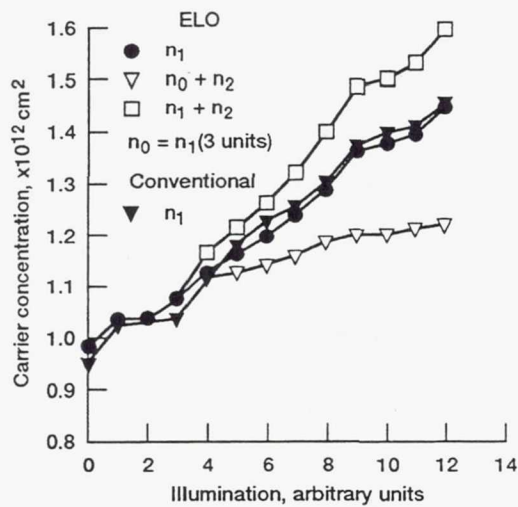Figure 4.—SdH waveforms for samples of Structure 2 after identical illumination.

Figure 5.—Ground subband concentration, n_1, and second subband concentration, n_2, derived from SdH measurements as a function of illumination in arbitrary units for ELO and conventional samples of Structure 2. The value n_0 corresponds to the ground subband contraction, n_1, at 3 units of illumination.
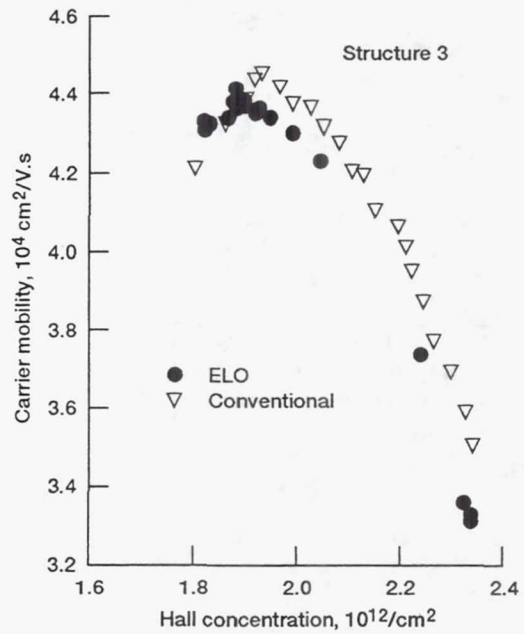

Figure 6.—Measured Hall mobility as a function of carrier concentration for an ELO and conventional sample of Structure 3.

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Transport properties of epitaxially lifted-off (ELO) films were characterized using conductivity, Hall and Shubnikov-de Haas measurements. A 10-15% increase in the 2D electron gas concentration was observed in these films as compared with adjacent conventional samples. We believe this result to be caused by a backgating effect produced by a charge build up at the interface of the ELO film and the quartz substrate. This increase results in a substantial decrease in the quantum lifetime in the ELO samples, by 17-30%, but without a degradation in carrier mobility. Under persistent photoconductivity, only one subband was populated in the conventional structure, while in the ELO films the population of the second subband was clearly visible. However, the increase of the second subband concentration with increasing excitation is substantially smaller than anticipated due to screening of the backgating effect.

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