Journal of Applied Physics

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Cite as: Journal of Applied Physics **72**, 1460 (1992); https://doi.org/10.1063/1.351708
Submitted: 09 September 1991 • Accepted: 11 May 1992 • Published Online: 17 August 1998

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Wide electron gas with periodic density modulation

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(Received 9 September 1991; accepted for publication 11 May 1992)

We report the growth and characterization of a high-quality wide (~2000 Å) three-dimensional electron gas (3DEG) with periodic density modulation (period ~200 Å) in a modulation-doped wide parabolic potential well with a superimposed superlattice. Computer-controlled molecular beam epitaxy is used to synthesize the potential well as a graded $Al_xGa_{1-x}As$ digital alloy. The density-modulated 3DEG is compared to a uniform 3DEG of the same average density and width in a parabolic well without the superlattice. The Al mole fraction profiles for the two samples are measured in calibration runs immediately prior to actual growths. The density-modulated 3DEG has a low-temperature in-plane mobility in excess of 10^5 $cm^2/V\,s$, compared to $\sim 2\times 10^5$ $cm^2/V\,s$ for the uniform 3DEG. Capacitance-voltage measurements directly reveal the modulation of the density of the electron gas in the parabolic well with superimposed superlattice, and the absence of any density modulation for the gas in the bare parabolic well.

I. INTRODUCTION

Applying a periodic potential to an electron gas gives rise to novel electrical properties arising from the creation of a superlattice (SL) band structure in the SL direction.[1] Periodic modulation of the density of an electron gas offers a system for the systematic study of collective excitations and interactions between electrons in different periods as the strength of the modulation is turned up from zero to a value high enough to break the continuous gas into unconnected layers of two-dimensional electron gases (2DEGs). Interactions between two 2DEGs in neighboring quantum wells separated by a thin barrier have recently been investigated.[2,3] An externally tunable periodic potential is usually applied in the plane of a 2DEG by lithographically or holographically patterning a periodic one-dimensional or two-dimensional array of connected metal gates on the sample surface.[4] Feature sizes in *e*-beam lithography and holography are currently limited to dimensions of several hundred Å, with the level of uncertainty and nonuniformity being of the same order of magnitude. Also, inasmuch as the patterned surface gate is spatially removed from the 2DEG by at least a few hundred Å, the induced lateral periodic potential is smoothed on the same length scale as this spatial separation.[4] The amplitude of this potential is therefore smaller than when the periodic potential is directly immersed in the electron gas itself. Smaller periods (~100 Å) can be obtained by incorporating a lateral superlattice (LSL) in or near a 2DEG at a GaAs/AlGaAs single interface grown on a vicinal GaAs surface.[5] The resulting periodic potential has manifested itself in anisotropic electron transport of the 2DEG parallel and perpendicular to the LSL,[5] but terrace-width nonuniformity and intermixing between the GaAs and AlGaAs components of the LSL[6] remain serious blocks to applying potentials of uniform period and large amplitude. Recently, cleaved edge overgrowth (CEO) has been used to realize a periodic potential (with small and uniform period) on a 2DEG, grown on the cleaved edge of an in-plane SL, and grown by conventional molecular beam epitaxy (MBE).[7] With a low-temperature mobility of $\sim 4\times 10^4$ $cm^2/V\,s$, this, like other CEO structures, offers exciting possibilities for the study of novel electronic properties arising from additional confinement and/or applied periodic potentials with length scales determined by MBE to atomic precision, but processing on 150 μm cleaved edges is nontrivial at this time. Direct immersion of a periodic potential in an electron gas has also been attempted in a SL with barriers that are selectively doped and thin enough that the electron states are extended in the growth direction [Fig. 1(a)].[8] But the scattering of electrons by the ionized donors in the barriers reduces the low-temperature in-plane mobility drastically.

Immersing the SL in a thick electron gas of high mobility produced by some other means than doping the SL barriers themselves suggests itself as a means of getting a high-mobility electron gas with a strong periodic potential. Such thick (~2000 Å) three-dimensional electron gases (3DEGs) have been produced in modulation-doped wide parabolic potential wells, in which the the 3D density is controlled by the curvature of the parabola.[9,10] A SL added to the parabolic well, as schematically illustrated in Fig. 1(b), is expected to modulate the density of the uniform 3DEG produced by the slowly varying parabolic potential.

A self-consistent solution of the Poisson–Schrödinger equation for this structure confirms this scenario [Fig. 2(a)]. The solution for a 2000-Å-wide parabolic well is shown for comparison [Fig. 2(b)], and is seen to produce a wide electron gas in the well fairly uniform at the curvature density $N_Q \sim 2.6\times 10^{16}$ cm^{-3}. With the addition of a SL, the electron density is modulated by as much as 50%. However, the energy spectrum for a single electron in the bare parabolic well is only slightly perturbed, for the SL period shown.

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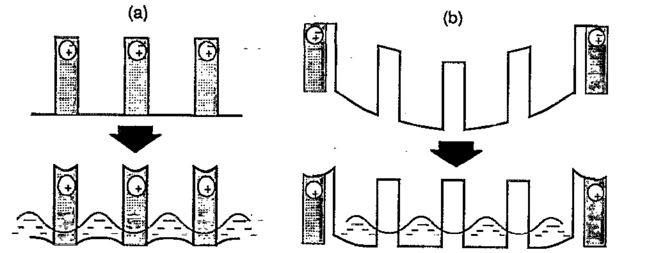

FIG. 1. (a) Modulation-doped superlattice (SL) with thin doped barriers used to produce an extended electron gas with periodic potential. (b) SL superimposed on a modulation-doped wide parabolic well to produce the same density modulation as in (a) on a wide electron gas of uniform density determined by the curvature of the parabola.

Such structures have been grown and their low-temperature transport properties measured,[11,12] and some of their electrical and optical properties calculated.[13] These transport measurements yield the energy spectrum, but afford only an indirect measure of the electron-density modulation. A more direct signature of this effect is needed. Such a measurement is presented below, along with other characterizations of the sample that highlight features of this design technique.

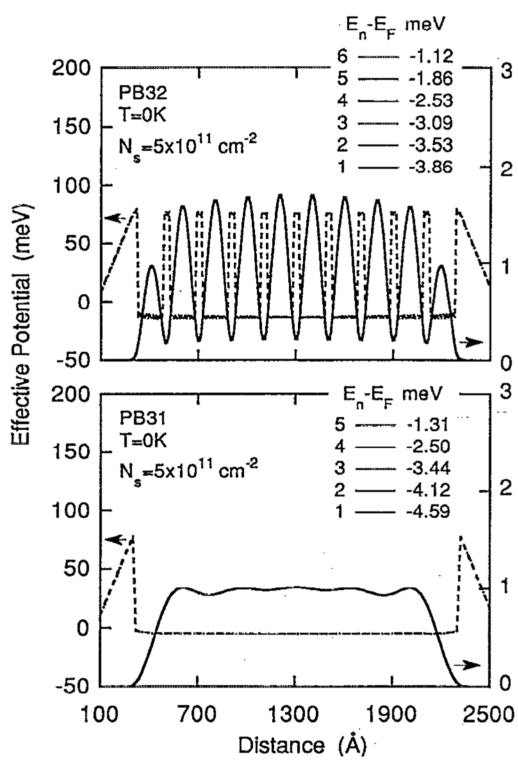

FIG. 2. Self-consistent potential and electron distribution for a wide parabolic well with SL (top) and without (bottom), showing the density-modulating effect of the SL. $N_Q = 2.61 \times 10^{16}$ cm^{-3} is the curvature of the parabola. While the uniform electron distribution (bottom) is strongly modified (top) by the SL, the energy eigenvalues are not substantially changed for the SL period shown. The Fermi energy E_F is the zero reference energy on the potential energy scale.

II. EXPERIMENTS AND DISCUSSION

Two samples, similar to the ones for which calculations were presented in Fig. 2, were grown by solid-source MBE: PB31, a modulation-doped 2000-Å-wide parabolic well, and PB32, a modulation-doped 2000-Å-wide parabolic well with a SL of 200 Å period superimposed. The two samples were identical in every respect, save for the density-modulating SL in PB32, and were grown one after the other to minimize system variations. The potential wells were realized as graded $Al_xGa_{1-x}As$ digital alloys,[14] i.e., by controlled pulsing of the Al beam in the presence of constant Ga and As beams incident on a semi-insulating GaAs substrate, which was held at 580 °C. The digital alloy is therefore itself composed of a fine SL, whose period was selected to be 20 Å, a value small enough for an electron to see a local average Al mole fraction x. The complete layer sequence for both samples is: 5000 Å GaAs buffer/2000 Å $Al_{0.3}Ga_{0.7}As$ buffer/40 Å $Al_{0.3}Ga_{0.7}As$ Si doped at 1.1×10^{18} cm^{-3}/200 Å $Al_{0.3}Ga_{0.7}As$ spacer/graded potential well/200 Å $Al_{0.3}Ga_{0.7}As$ spacer/40 Å $Al_{0.3}Ga_{0.7}As$ Si doped at 1.1×10^{18} cm^{-3}/170 Å $Al_{0.3}Ga_{0.7}As$ Si doped at 5×10^{17} cm^{-3}/2000 Å $Al_{0.3}Ga_{0.7}As$ cap/100 Å GaAs cap. The $Al_xGa_{1-x}As$ in the 2000-Å-wide parabolic wells of PB31 and PB32 was varied quadratically from GaAs at the well center to $Al_{0.2}Ga_{0.8}As$ at the well edges, jumping abruptly to the barrier $Al_{0.3}Ga_{0.7}As$ there. The bigger SL in the parabolic well of PB32 has a period of 200 Å, composed of a 160-Å-wide well and a 40-Å-wide barrier, with Δx_{Al} between the well and barrier being 0.1. All widths of the big SL are integer multiples of the finer digital-alloy SL period of 20 Å.

The variation of Al mole fraction versus depth in the graded potential wells was measured in a calibration run immediately prior to actual sample growth. The variation of the collector current of an ion gauge used in place of the substrate was monitored as a function of time as the Al beam was pulsed with the same controlled sequence as for the subsequent actual growth.[15] The Al mole fraction profiles for both samples (Fig. 3) show fairly small deviations from the design profiles and testify to the level of control achievable in digital alloys to obtain these complex potentials.

Cloverleaf pattern Van der Pauw mesas were etched on both samples, and indium was alloyed to the ohmic-contact pads. Hall measurements were performed in a cold-finger cryostat from 300 to 10 K, and in liquid He (4.2 K). The variation of the in-plane mobility (μ) and electron sheet density (N_s) with temperature is shown for both samples in Fig. 4. The reduced ionized-impurity scattering at low temperatures resulting from the spatial separation of the electrons in the well from the donors in the barriers surrounding the parabolic well results in μ(4.2 K) as high as 1.8×10^5 cm^2/V s at N_s(4.2 K)$=2.5 \times 10^{11}$ cm^{-2} for the bare parabolic well, and μ(4.2 K)$=1.1 \times 10^5$ cm^2/V s at N_s(4.2 K)$=2.0 \times 10^{11}$ cm^{-2} for the parabolic well with superimposed SL. The low-temperature mobility for the density-modulated 3DEG is an order of magnitude higher than was obtained in a modulation-doped SL of the type shown in Fig. 1(a).[8] Since the samples were grown

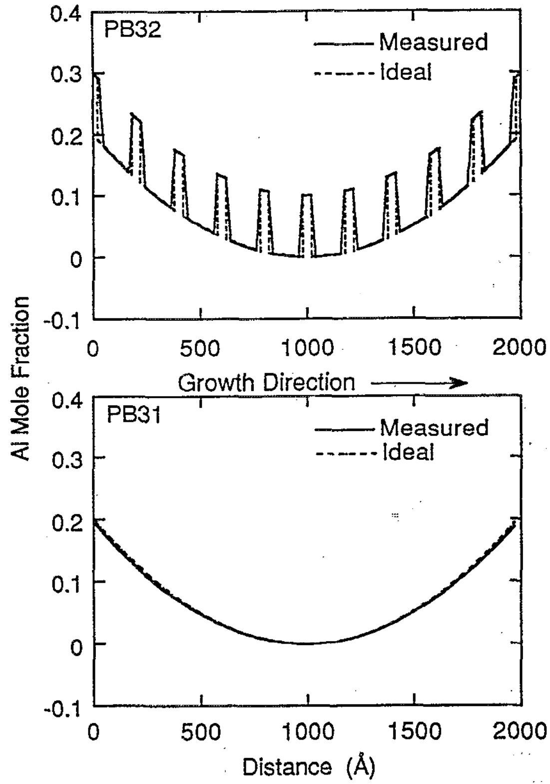

FIG. 3. Ion-gauge measured Al mole fraction profiles for wide parabolic well with SL (top) and without (bottom), for a MBE-grown digital AlGaAs alloy composed of a fine SL of 20 Å period. The slight tilt of the walls of the SL (top) is due to the 20 Å resolution of the measurement, and not an intrinsic limitation.

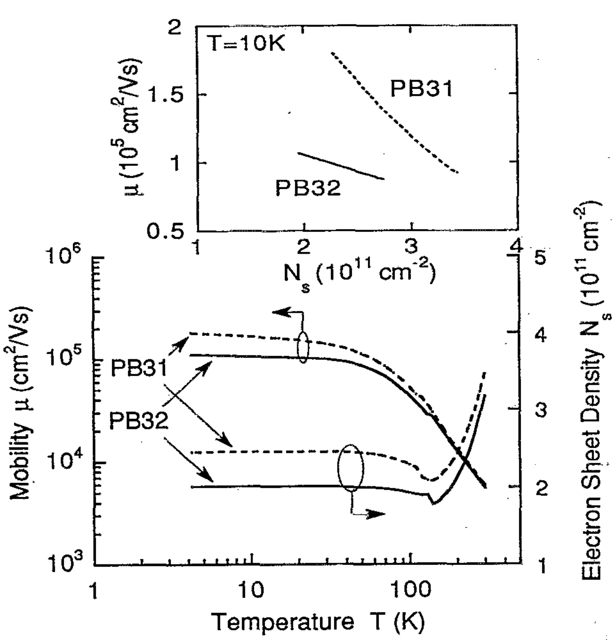

FIG. 4. Mobility vs temperature for both samples, showing the benefits of modulation doping at low temperature. Inset shows mobility of both samples decreasing with increasing electron sheet density at $T=10$ K.

one right after the other, and the densities N_s(4.2 K) are comparable, the difference in μ(4.2 K) must be attributed at least partly to the greater Al content in PB32 with its attendant enhanced alloy-disorder scattering. $\mu_{\text{alloy-disorder}}$ being inversely proportional to $\int x(1-x)dz$,[16] the higher x_{avg} of 0.037 for PB32 over the extent of the electron gas, when compared to 0.017 for PB31 over the same extent, implies a reduction in mobility by a factor of ~ 1.7 on addition of the SL to the bare parabolic well just from this effect. The roughness of the walls of the 160-Å-wide wells in the SL is an important issue.[17] For a single quantum well of this width and infinite potential depth, the interface-roughness scattering limited mobility is in excess of 10^6 cm^2/V s.[17] The coupling between the SL wells through the 40-Å-wide barriers should increase this estimate even further, and suggests that for this structure, interface roughness is not a critical issue. The mobility for both samples decreases with increasing electron sheet density (inset in Fig. 4) at a fixed temperature $T=10$ K, probably a result of the spread of the electron distribution from the center into regions of more Al mole fraction at the well edges with the attendant enhanced alloy-disorder scattering there.

Ti/Au (200 Å/2000 Å) was then evaporated on the mesas and the small-signal capacitance versus voltage (C-V) measured between the surface gate and the electron gas in the graded well, for both samples, using standard lock-in techniques. The results were found to be independent of ac-voltage frequency, dc-voltage-bias sweep rate, and sweep direction. C-V profiles ($T=4.2$ K) for both samples are shown in the inset in Fig. 5. Two features are apparent in these profiles. First, the capacitance falls off, with more negative gate bias, from zero bias to threshold (where all the electrons are depleted from the well), for both samples. This decrease is mainly attributed to the increased spacing between the two plates of the parallel-plate capacitor formed by the surface metal gate and the electron gas in the well, respectively, as the leading edge of the gas is pushed deeper toward the substrate with more negative voltage bias at the gate.[18] Furthermore, whereas the capacitance falls off smoothly with voltage for the bare parabolic well (PB31), the C-V profile for the parabolic well with SL (PB32) displays ripples superimposed on the decrease. These ripples are associated with the sweeping of the leading edge of the electron gas through successive periods of the SL with more negative bias. In both cases, there is concurrent depopulation of the subbands occupied by the electron gas, but the ripples expected in the C-V traces from this effect are calculated to be small,[19] a fact that is experimentally underscored by the relative absence of ripples in the C-V trace for the parabolic well. From the C-V measurement, one can extract an apparent electron distribution versus depth using $\tilde{N}(z)=2/q\epsilon_u[d(1/C^2)/dV]^{-1}$ as the apparent electron density at the apparent depth $z=\epsilon_u/C$, where C is the capacitance per unit area between surface gate and electron gas at voltage bias V, and ϵ_u is the uniform permittivity assumed.[20] Using $\epsilon_u=12.2$ (of the $Al_{0.3}Ga_{0.7}As$ cap), we arrive at the apparent electron profiles shown in Fig. 5 for both samples. A modulation of the apparent electron density is readily seen for the electron

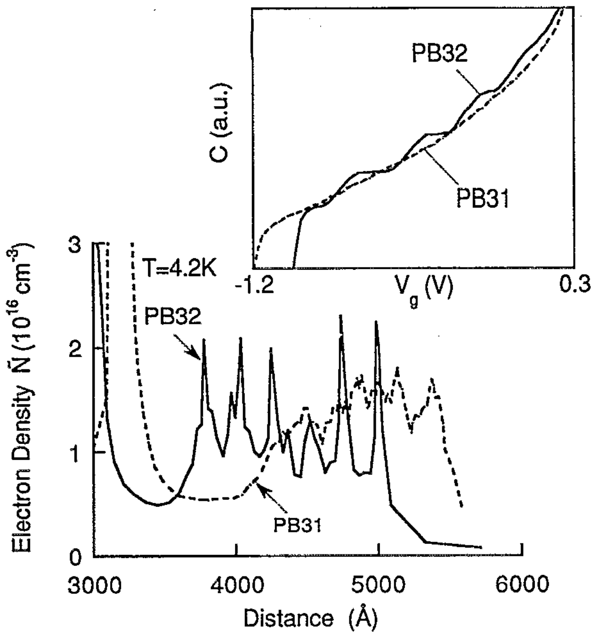

FIG. 5. 4.2 K apparent-electron-density distributions extracted from the *C-V* traces (inset) show strong density modulation of the electron gas in the parabolic well with SL (PB32) and the relative absence of modulation for the parabolic well without SL (PB31) (the sensitivity of the technique allowing us to measure the unintentional nonuniformities in the well curvature at the level that can be achieved with current MBE technology). The effect of the SL on electron distribution is most directly seen in the *C-V* traces in inset. Threshold gate voltage for both samples ~ -1 V.

gas in the parabolic well with superimposed SL; no such modulation is seen for the 3DEG in the bare parabolic well. The average periodicity of the apparent-electron-density modulation in the *C-V* measurement is ~230 Å, in reasonable agreement with the nominal SL period of 200 Å. We believe this to be the most direct evidence to date of the density modulation produced in such structures.

III. CONCLUSIONS

In summary, we have fabricated a high-mobility 3DEG with periodic density modulation using computer-controlled MBE to make a digital AlGaAs alloy with accurate Al mole fraction variation. This variation is directly measured with an ion gauge, and the resulting periodic modulation of the electron density is directly seen in a simple capacitance-voltage measurement. An attractive feature of this technique is the possibility of applying periodic potentials to high-mobility electron gases of different shapes. The average-density profile is defined by the curvature of a wide potential well; density modulation is achieved with a SL of narrower period inserted in this wide well. More complex electron density distributions can, of course, be achieved with the appropriate Al mole fraction profiles in digital $Al_xGa_{1-x}As$ alloys.

ACKNOWLEDGMENTS

We thank J. H. English, M. S. Sherwin, E. G. Gwinn, G. Snider, and K. Campman of UCSB, R. M. Westervelt, A. J. Rimberg, and J. Baskey of Harvard University, and K. Ensslin of Universität München, for valuable discussions. This research was supported by the United States Air Force Office of Scientific Research.

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