Selectively δ-doped $Al_xGa_{1-x}As/GaAs$ heterostructures with high two-dimensional electron-gas concentrations $n_{2DEG} \geqslant 1.5 \times 10^{12}$ cm^{-2} for field-effect transistors

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The δ-doping concept is applied to selectively doped heterostructures in the $Al_xGa_{1-x}As/GaAs$ material system. High two-dimensional electron-gas concentrations $\geqslant 1.5 \times 10^{12}$ cm^{-2} are obtained at $T = 300$ K in such selectively δ-doped heterostructures due to (i) size quantization in the $Al_xGa_{1-x}As$ and (ii) localization of donor impurities within one atomic monolayer. Shubnikov–de Haas measurements yield $n_{2DEG} = 1.1 \times 10^{12}$ cm^{-2} at 300 mK and at a spacer thickness of 25 Å. Selectively δ-doped heterostructure transistors (SΔDHT's) are fabricated and have excellent characteristics due to the enhanced electron-gas concentrations achieved. A very high transconductance of $g_m \cong 360$ mS/mm at a gate length of 1.2 μm is obtained in depletion-mode SΔDHT's at $T = 300$ K.

The seminal concept of selectively doped heterostructures was introduced nearly ten years ago.[1] The unique properties of these heterostructures are the quasi-two-dimensional electron gas (2DEG) at the $Al_xGa_{1-x}As/GaAs$ interface[2] and high carrier mobility.[3–7] Both fundamental and applied research have been stimulated by the invention of selectively doped heterostructures, giving rise to the observation of the fractional quantization of Hall effect[8] and the fabrication of selectively doped heterostructure transistors.[9–11]

The concept of δ-doping allows us to localize donor or acceptor impurities within one monolayer of the host semiconductor crystal[12] giving rise to size quantization in a V-shaped quantum well.[13] Very high electron concentrations exceeding 10^{13} cm^{-2} have been obtained in δ-doped GaAs.[12] The δ-doping technique is very interesting because it represents the ultimate technological limit of impurity profiles; the technique has resulted in a series of novel electronic[14] and photonic[15] devices.

In the present work we combine the δ-doping concept with the concept of selectively doped heterostructures. We show that such selectively δ-doped heterostructures (SΔDH's) can have high concentrations of the 2DEG, which are *not* achievable in conventional, homogeneously doped heterostructures. We will first describe the basic structure of the SΔDH, then demonstrate the high concentration of the 2DEG by Shubnikov–de Haas and Hall measurements, and finally present the novel selectively δ-doped heterostructure transistor (SΔDHT).

The molecular beam epitaxial growth of the new structure formed by δ doping will be reported by Cunningham *et al.*[3] The investigations include the quantum Hall effect and variable temperature mobility. The results show that enhancements in interface densities are achievable, and further, there is potential for very high mobility.

The energy-band diagrams of the new SΔDH and the conventional SDH are shown in Figs. 1(a) and 1(b), respectively. In the SΔDH [Fig. 1(a)], all donor impurities are localized in a plane at a distance W_s from the $Al_xGa_{1-x}As/GaAs$ interface. This unique donor localization results in a V-shaped quantum well with a lowest subband energy of E_0^δ. In the conventional SDH, the $Al_xGa_{1-x}As$ conduction band has a parabolic shape [Fig. 1(b)] with negligible size quantization. For the *selectively δ-doped heterostructures* (SΔDH's) we can write the energy balance, $\Sigma E = 0$: SΔDH:

$$\sum E = -E_0 - (E_F - E_0) + \Delta E_c - qEW_S + E_0^\delta + (E_F - E_0^\delta), \qquad (1)$$

where E_0 is the lowest subband energy of the 2DEG, $(E_F - E_0)$ is its degeneracy, ΔE_c is the conduction-band discontinuity, E_0^δ is the lowest eigenstate energy in the V-shaped quantum well of the $Al_xGa_{1-x}As$, $(E_F - E_0^\delta) = 0$ (no mobile carriers in the $Al_xGa_{1-x}As$), and E is the elec-

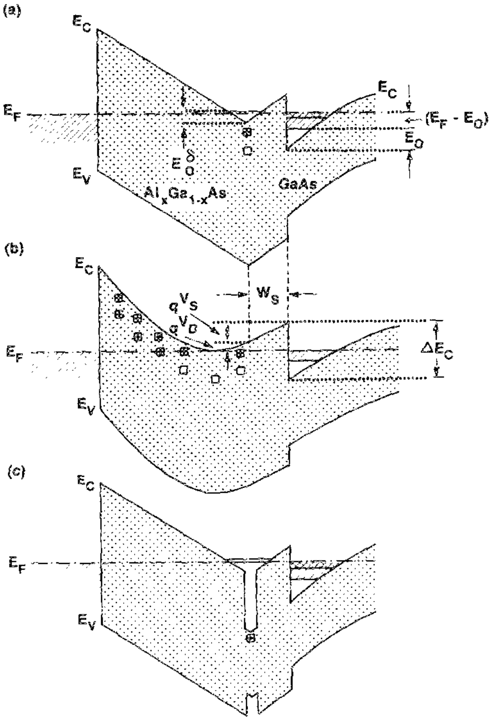

FIG. 1. Energy-band diagram of a (a) selectively δ-doped heterostructure and a (b) homogeneously doped heterostructure. A heterostructure (c) which is δ doped in a GaAs quantum well avoids persistent photoconductivity.

tric field within the spacer. In Eq. (1) we assume that none of the two quantum wells (V-shaped quantum well in the $Al_xGa_{1-x}As$, and triangular well at the semiconductor interface) perturbs the eigenstate energy of the other corresponding quantum well. For the (*homogeneously*) *selectively doped* heterostructure (SDH) we can write the following sum of energies, $\sum E = 0$:

$$\sum E = -E_0 - (E_F - E_0) + \Delta E_c - q\mathcal{E}W_s - qV_D, \qquad (2)$$

where V_D is the potential drop within the depletion region, as shown in Fig. 1(b). Comparison of Eqs. (1) and (2) yields two results. First, in the SΔDH [see Eq. (1)], the eigenstate energy in the V-shaped quantum well of the $Al_xGa_{1-x}As$, E_0^δ, adds up to the barrier height, ΔE_c. Therefore, we can understand the sum $(E_0^\delta + \Delta E_c)$ as an "*effective conduction-band discontinuity*" which is *enhanced* as compared to the conventional SDH. Second, the potential drop in the depletion region [see Eq. (2)], $-qV_D$, does *not* enter Eq. (1). The depletion width approaches zero due to the *localization of donor impurities* in the δ-doped $Al_xGa_{1-x}As$. The SΔDH has consequently two advantages: (i) effective discontinuity enhancement due to size quantization in the $Al_xGa_{1-x}As$; (ii) absence of depletion-region potential drop due to localization of donor impurities in the δ-doped $Al_xGa_{1-x}As$. Both characteristics will result in the desired increase of the concentration of the 2DEG. Before we calculate the carrier concentration of the 2DEG, we would like to draw the attention of the reader to Fig. 1(c). This structure uses a GaAs quantum well which is δ doped. If the GaAs quantum well is thin enough (< 10 Å), the eigenstate energy in the $Al_xGa_{1-x}As$ is not influenced significantly. Such a structure would maintain the advantages of the SΔDH and, in addition, would reduce the problem of persistent photoconductivity associated with the "deep donor" in the $Al_xGa_{1-x}As$[16] by spatially separating donors from the $Al_xGa_{1-x}As$.[17]

Simple quantum mechanical and electrostatic considerations allow us to replace the energy terms of Eqs. (1) and (2) by terms that depend on the two-dimensional electron-gas concentration n_{2DEG} only.

$$E_n = \tfrac{1}{2}\,(n+1)^{2/3}\,(q^2 2\pi\hbar n_{2DEG}/\epsilon_2\sqrt{m^*})^{2/3}$$
$$\text{with } n = 0,1,\ldots, \qquad (3)$$

$$E_F - E_0 = k_B T \ln[\exp(n_{2DEG}/k_B T D_{2D}) - 1], \qquad (4)$$

$$\text{with } D_{2D} = m^*/(\pi\hbar^2), \qquad (5)$$

$$\Delta E_c = (2/3)\Delta E_g \qquad (6)$$

$$\mathcal{E} = (q/\epsilon_1) n_{2DEG} \qquad (7)$$

$$E_n^\delta = 2^{-7/3}(n+1)^{2/3}(q^2 2\pi\hbar N_D^{2D}/\epsilon_1\sqrt{m^*})^{2/3}, \qquad (8)$$

$$E_F - E_0^\delta = 0, \qquad (9)$$

$$qV_D = q^2 n_{2DEG}^2/2\epsilon_1 N_D. \qquad (10)$$

Inserting Eqs. (3)–(10) into Eqs. (1) and (2) yields equations of third order, which depend on n_{2DEG} only. The resulting equations can be solved graphically. As shown in Fig. 2 the solutions for n_{2DEG} are obtained as the intersection of the solid and dashed curves. With an Al mole fraction of $x = 0.30$ ($\Delta E_c = 250$ meV) and a spacer thickness of $W_s = 50$ Å, a 2DEG concentration of $n_{2DEG} = 10.4\times10^{11}$ cm^{-2} is obtained for the homogeneously doped ($N_D = 2\times10^{18}$ cm^{-3}) heterostructure. A significantly higher concentration of $n_{2DEG} = 19.6\times10^{11}$ cm^{-2} is obtained for the δ-doped ($N_D^{2D} = 5\times10^{12}$ cm^{-2}) heterostructure, demonstrating the advantage of selectively δ-doped heterostructures. Although the present calculation is simplified in some respect (e.g., deep donor contribution[16] neglected), the calculation shows the basic effect of concentration enhancement.

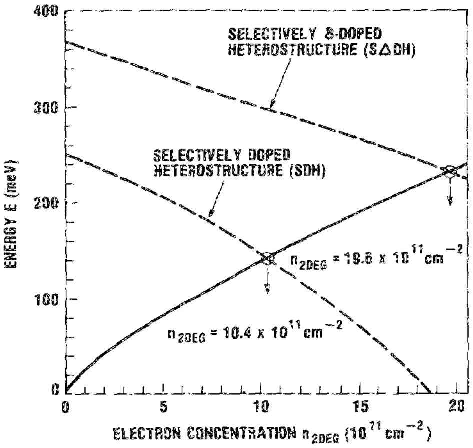

FIG. 2. Graphic solution for carrier concentrations in a selectively δ-doped heterostructure (SΔDH) ($n_{2DEG} = 19.6\times10^{11}$ cm^{-2}) and a homogeneously doped heterostructure (SDH) ($n_{2DEG} = 10.4\times10^{11}$ cm^{-2}).

The heterostructures are grown in a molecular beam epitaxy system. The SΔDH's consist of a 1-μm-thick undoped GaAs buffer layer, an undoped 25-Å-thick $Al_xGa_{1-x}As$ spacer, the n-type δ-doped sheet of concentration $N_D^{2D} = 5\times10^{12}$ cm^{-2}, followed by a 375-Å-thick n-type $Al_xGa_{1-x}As$ layer. For the field-effect transistors a 750-Å-thick n^+-type GaAs top layer ($N_D = 1\times10^{19}$ cm^{-3}) is included. The SΔDHT has a gate width of 150 μm, a gate length of 1.2 μm (mask dimension of 1.0 μm), and a source-drain spacing of 4 μm.

The magnetoresistance of a SΔDH is shown in Fig. 3(a). Shubnikov–de Haas oscillations with two distinct periods are observed. We attribute the two oscillations to the lowest and first excited subbands of the 2DEG. The population of two subbands has hitherto not been observed in $Al_xGa_{1-x}As$ heterostructures at spacer thicknesses of 25 Å. The concentrations within the two subbands are evaluated by plotting the Landau quantum numbers of the minima (solid circles) and maxima (open circles) versus reciprocal magnetic induction, as shown in Fig. 3(b). The slope of this plot yields the concentrations of 9.7×10^{11} cm^{-2} and 1×10^{11} cm^{-2} for the lowest and first excited subbands, respectively. The total concentration is then $n_{2DEG} = 1.07\times10^{12}$ cm^{-2} at 300 mK. The corresponding mobility is $\mu = 37\,000$ cm^2/V s. At room temperature a concentration of $n_{2DEG} = 1.7\times10^{12}$ cm^{-2} and a mobility of 8900 cm^2/V s have been obtained from Hall measurements.

Selectively doped heterostructure transistors have typical concentrations of $n_{2DEG} \leqslant 1\times10^{12}$ cm^{-2}. It is difficult to obtain higher concentrations in the material system $Al_xGa_{1-x}As$/GaAs by homogeneous doping. The high 2DEG concentration that can be obtained in the selectively δ-doped heterostructures is favorable for field-effect transis-

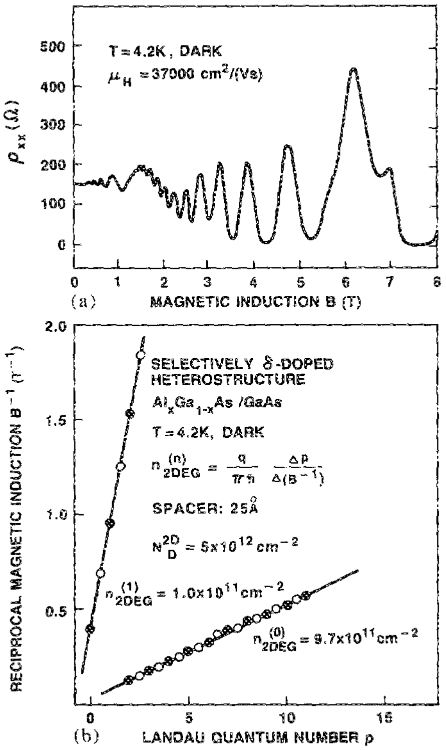

FIG. 3. (a) Low-temperature magnetoresistance of a selectively δ-doped heterostructure. (b) Evaluation of the two periods of the Shubnikov–de Haas oscillations yields a concentration of 9.7×10^{11} and 1×10^{11} cm^{-2} for the lowest and first excited subbands, respectively.

tor performance. In Fig. 4 we show the output characteristics of two *depletion-mode* SΔDHT's. The SΔDHT's have low ON resistance ($R_{ON} = 1.83$ Ω mm), excellent saturation characteristics, low differential output conductance in the saturation regime, and good pinch-off characteristics. A very high transconductance of up to $g_m = 360$ mS/mm is obtained from the SΔDHT. A transconductance of 320–360 mS/mm is measured in a considerable number of SΔDHT's on the same wafer. The processed wafers have good homogeneity and yield. The contact resistance is measured to be $R_{cl} = 0.07$ Ω mm. At a low temperature of $T = 77$ K a transconductance of $g_m = 420$ mS/mm is obtained. The lower part of Fig. 4 shows the gate-source current-voltage characteristic. A large breakdown voltage of $V = -6$ V is measured in the reverse direction.

In conclusion, a novel selectively δ-doped heterostructure is proposed. The high concentration of the two-dimensional electron gas is shown to be due to (i) the quantum-size effect in the δ-doped region of the Al$_x$Ga$_{1-x}$As, and due to (ii) the spatial localization of donor impurities. The calculation of the carrier concentration yields an enhancement in the SΔDH. The high carrier concentration is confirmed by Shubnikov–de Haas measurements ($n_{2DEG} = 1.1\times10^{12}$ cm^{-2}, $\mu = 37\,000$ cm^2/V s) and by Hall effect at 300 K ($n_{2DEG} = 1.7\times10^{12}$ cm^{-2}, $\mu = 8900$ cm^2/V s). SΔDHT's have improved characteristics due to the high electron-gas concentration. Very high transconductances of $g_m \cong 360$ mS/mm have been obtained from SΔDHT's with a gate length of $L_g = 1.2\,\mu$m.

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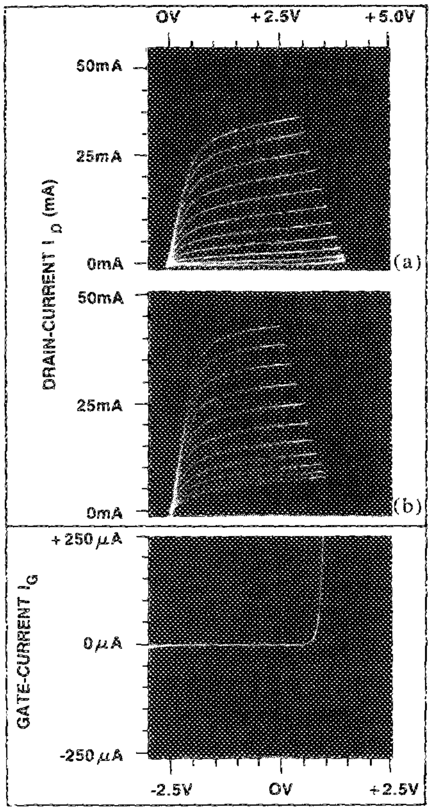

FIG. 4. Drain current vs drain-source voltage of a selectively δ-doped heterostructure transistor with a transconductance of (a) 327 mS/mm (at $V_g = +0.3$ V; top trace: $V_g = +0.5$ V; $V_g = 100$ mV/step) and (b) 347 mS/mm (at $V_g = +0.2$ V; top trace: $V_g = +0.5$ V; $V_g = 100$ mV/step). A gate-source current voltage characteristic is shown in the lower part.

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