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Breakdown Voltage Enhancement from Channel Quantization in InAlAs/n$^+$-InGaAs HFET's

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***Abstract*—$In_{0.52}Al_{0.48}As/n^+$-$In_{0.53}Ga_{0.47}As$ HFET's have been fabricated with different channel thicknesses. We show that by reducing the channel thickness from 350 to 100 Å, the reverse gate breakdown voltage improves from 9 to 19 V. We partially attribute this to the increased effective bandgap that results from energy quantization in the channel. This bandgap enhancement is directly confirmed by photoluminescence (PL) measurements on the same heterostructures. Channel quantization emerges as a promising approach for exploiting the excellent transport properties of InGaAs with high InAs mole fraction. The principle behind our work should be applicable to other narrow-gap semiconductors.**

$In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ heterostructure field-effect transistors (HFET's) on InP are of great interest for long-wavelength optical and ultrahigh-frequency microwave telecommunications applications. The advantages of this material system are many. $In_{0.53}Ga_{0.47}As$ has a higher peak electron velocity and a higher room-temperature mobility than GaAs. In addition, it has a larger Γ-L separation and a lower effective mass [1].

Enriching the InAs mole fraction of $In_{0.53}Ga_{0.47}As$ results in HFET's with superior transport properties. However, this comes at the cost of a severely reduced breakdown voltage V_B, presumably through the decrease in the energy gap E_g [2]. A method of increasing the effective energy gap in the channel is to introduce energy quantization by reducing the channel thickness to dimensions comparable to the electron wavelength (Fig. 1) [3]. In fact, it has been shown in $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum wells that the photoluminescence emission wavelength decreases [4], [5] with a reduction in well thickness.

In this work, we exploit this effect to enhance the breakdown voltage of $In_{0.52}Al_{0.48}As/n^+$-$In_{0.53}Ga_{0.47}As$ HFET's on InP. We have doubled V_B by shrinking the $In_{0.53}Ga_{0.47}As$ channel thickness from 350 to 100 Å, keeping other physical parameters constant. The principle behind our work should allow one to better exploit the excellent transport properties of InAs-rich InGaAs [2] and other promising narrow-gap semiconductors like InAs and InSb [6], [7].

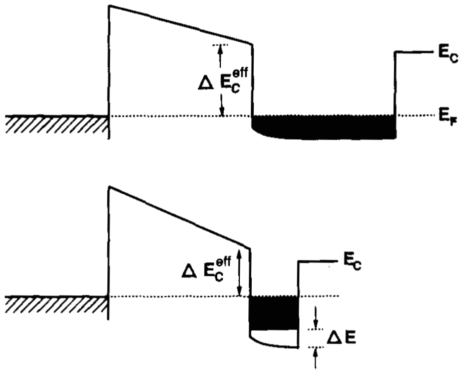

Fig. 1. Schematic conduction band diagrams in equilibrium of InAlAs/n$^+$-InGaAs HFET's for thick and thin channels, showing the increase in effective energy gap in the thinner channel.

A cross section of the device structure is shown in Fig. 2. In essence, this device is a doped-channel HFET with an undoped pseudoinsulator [8]. The device structure consists (from bottom to top) of a 1000-Å undoped $In_{0.52}Al_{0.48}As$ buffer layer, a channel consisting of an undoped $In_{0.53}Ga_{0.47}$ As layer and a 100-Å heavily Si-doped (nominal $N_D = 4 \times 10^{18}$ cm^{-3}) $In_{0.53}Ga_{0.47}As$ layer, a 300-Å undoped $In_{0.52}Al_{0.48}As$ gate insulator layer, and an undoped 50-Å $In_{0.53}Ga_{0.47}As$ cap. The wafers were grown on Si-InP by MBE in M.I.T.'s Riber 2300 system. In an effort to keep the channel charge constant, the thickness of its undoped portion was varied while the thickness of its heavily portion was kept constant at 100 Å. Four wafers were subsequently grown with subchannel thicknesses of 250, 100, 50, and 0 Å, i.e., total channel thicknesses of 350, 200, 150, and 100 Å. Devices were fabricated with nominal gate lengths of 1 μm and widths of 30 μm. Fabrication is similar to that used in [8].

Our baseline device, 200-Å channel thickness, had a peak transconductance $g_{m(\text{peak})}$ of 202 mS/mm and a maximum drain current $I_{d(\max)}$ of 312 mA/mm. The output conductance g_d was 5.73 mS/mm, resulting in a voltage gain A_V of 35.

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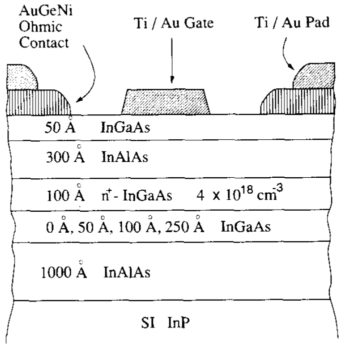

Fig. 2. Cross section of grown device structures.

These are average values over five devices. $g_{m(\text{peak})}$ and $I_{d(\max)}$ were measured at $V_{ds} = 4$ V, and g_d at $V_{ds} = 4$ V and $V_{gs} = 0$ V. The contact and channel sheet resistances, measured by TLM, are 0.37 Ω · mm and 625 Ω/□, respectively.

The reverse gate breakdown voltage V_B was measured with the source and drain grounded, and was defined at a reverse gate current of 500 μA, corresponding to about 5% of the peak drain current of our baseline device [2]. Detailed device results are presented elsewhere [9]. Here we focus on our main result: the increased breakdown voltage in devices with thinner channels and the experimental confirmation of the energy quantization therein.

Fig. 3 shows typical reverse gate I-V characteristics of HFET's as a function of channel thickness. As shown, V_B increases gradually from 9 V at a channel thickness of 350 Å to 10.6 V at 200 Å, 11.9 V at 150 Å, and to 19.1 V at 100 Å. Average V_B measurements over several devices are within 1 V of the typical values shown in Fig. 3. V_B for the 200-Å channel is also similar to what we have previously measured in identical devices grown and processed separately [2]. The drastic improvement in breakdown voltage of our quantized-channel HFET's is a significant merit for high-power applications. This is particularly so in this material system because typical InAlAs/InGaAs MODFET breakdown voltages are on the order of 5 V [10], [11].

In order to verify the bandgap enhancement in the channel as a result of carrier quantization, we have carried out photoluminescence (PL) measurements on unprocessed portions of the device samples at 77 K. The results are shown in Fig. 4. The energy of the peak PL intensity increases from 0.83 eV for the 350-Å channel to 0.86 eV for the 200-Å channel, 0.88 eV for the 150-Å channel, and 0.92 eV for the 100 Å-channel. The literature reports a temperature-independent PL energy shift of about 60 meV over the $In_{0.53}Ga_{0.47}As$ bulk value for 100-Å-thick $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ quantum wells [4], [5]. This value of 60 meV is also consistent with simple calculations for a finite square well of thickness 100 Å. Our slightly larger shift of 90 meV in the 100-Å channel might be due to depletion at the top and possibly bottom interfaces, causing a reduced effective well thickness. Additionally, band bending in the insulator results in an effective stronger potential than a square well (Fig. 1).

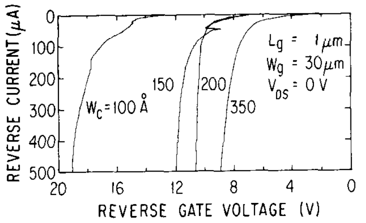

Fig. 3. Breakdown voltage V_B for typical HFET's with channel thicknesses of 100, 150, 200, and 350 Å.

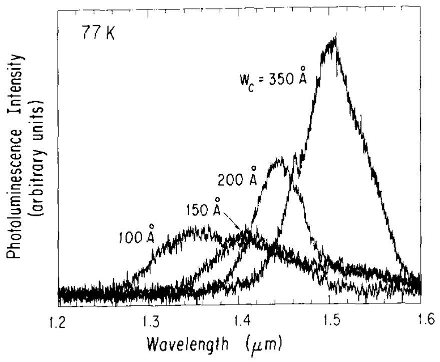

Fig. 4. PL spectra of the device heterostructures, showing an increase in PL energy with decreasing channel thickness.

Both effects will tend to enhance the strength of carrier quantization over a simple quantum well.

Electron quantization, as schematically shown in Fig. 1, also implies a reduction of the effective conduction-band discontinuity between channel and metal gate. This, in return, is expected to result in enhanced forward gate leakage current. We have experimentally found this to be the case at 300 and 77 K [9], providing us in this manner with an independent confirmation of the presence of quantization in the channel.

Unfortunately, we have found that a reduction in the channel thickness results in the degradation of transconductance and peak drain current [9]. $g_{m(\text{peak})}$ decreases from 262 to 138 mS/mm, and $I_{d(\max)}$ from 451 to 208 mA/mm in going from a channel thickness of 350 to 100 Å. However, the output conductance g_d improves due to the enhanced channel aspect ratio, decreasing from 10.8 to 1.84 mS/mm. This results in an enhancement in the voltage gain A_V from 24 to 75. The degradation in $g_{m(\text{peak})}$ and $I_{d(\max)}$ results from an increased source resistance R_s, a reduced channel sheet charge concentration n_s, and degraded mobility μ. From 350 to 100 Å, R_s increases from 1.4 to 2.7 Ω · mm, n_s drops from 2.38×10^{12} to 1.77×10^{12} cm^{-2}, and μ decreases from 4318 to 3591 cm^2/V · s. n_s and μ were measured by the Hall effect. The acknowledged poor quality of the reverse InGaAs/InAlAs interface at the back of the channel can be held responsible for the mobility reduction [12], [13]. As the undoped subchannel is thinned down, the reverse interface has a larger impact on carrier mobility since the channel electrons travel closer to the reverse InAlAs/InGaAs interface. There are, however, techniques that could mitigate this degradation: superlattice buffers to improve mobility [13] and the migration-enhanced epitaxy (MEE) growth technique to reduce interface roughness [14].

Thinning down the subchannel results in a reduction of sheet carrier concentration, possibly from backside depletion. A reduced channel doping can also result in an improvement of breakdown voltage. In a separate experiment on similar devices (with 200-Å channel thickness), we examined the impact of channel doping on V_B. This experiment indicated that a reduction in sheet charge concentration from 2.38×10^{12} to 1.77×10^{12} cm^{-2} should result in an improvement of V_B by 5 V. Our experimental observation of a 10-V improvement in going from a 350- to 100-Å channel is evidence that quantization is instrumental in drastically enhancing the breakdown characteristics of our HFET's.

In conclusion, $In_{0.52}Al_{0.48}As/n^+\text{-}In_{0.53}Ga_{0.47}As$ HFET's have been fabricated with channel thicknesses of 100, 150, 200, and 350 Å. For devices with channel thicknesses of 100 Å, the breakdown voltage improved twofold over the 350-Å devices. This is postulated to partially arise from an enlargement of the effective energy gap caused by energy quantization introduced from electron confinement, as observed by PL.

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