Physics of breakdown in InAlAs/InGaAs MODFETs

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InAlAs/InGaAs MODFETs have achieved record high-frequency and low-noise performance. They are promising candidates for applications in microwave and lightwave communication systems. Their main weakness, however, has been their low breakdown voltage (BV) which severely limits their applications. Considerable work has focussed on improving BV of these devices. Recently, BV up to 10 V has been demonstrated [1] by using a combination of surface-depleted InGaAs cap, mesa-sidewall isolation, and Si_3N_4 passivation layer. These devices offer a unique opportunity to explore the intrinsic physics of breakdown and assess the ultimate potential of InAlAs/InGaAs MODFETs for power applications.

In this abstract, we present a detailed study of the physics of off-state breakdown in state-of-the-art lattice-matched and pseudomorphic InAlAs/InGaAs MODFETs. We find that, similarly to heterojunction avalanche photodiodes, breakdown in these devices is a two-step process. First, electrons are injected from the gate into the channel through thermionic-field emission. Second, because of the large conduction-band offset and the electric-field in the insulator, these electrons enter the channel hot and immediately relax their energy through impact-ionization. Both steps are important in the breakdown process.

The heterostructures have a superlattice buffer, an $In_xGa_{1-x}As$ channel with x=0.52 (lattice-matched), 0.62 or 0.70 (pseudomorphic), a delta-doped InAlAs pseudoinsulator and an InGaAs cap. MODFETs (L_G=0.28 μm, W_G=60 μm) had V_T = -0.6 V, f_t=83, 87, 93 GHz, f_{max}= 140, 150, 180 GHz, $g_{m(PEAK)}$= 400, 450, 550 mS/mm, and $I_{D(MAX)}$= 275, 290, 350 mA/mm for x=0.52, 0.62, and 0.70 respectively.

We carried out three-terminal off-state BV measurements by using our newly formulated Drain-current Injection technique. With the source grounded, current (1 mA/mm) is injected into the drain of the on-state device. The gate is then ramped to shut the device off while V_{DS} and I_G are monitored. The drain-source breakdown voltage, BV_{DS} was defined as the peak V_{DS} and the drain-gate breakdown voltage, BV_{DG} was defined at I_D=-I_G (I_S=0).

At 300 K, BV_{DS} was 8.9 V, 6.3 V, and 5.1 V for x=0.53, 0.60, and 0.70 respectively. These are record values in this material system. In all devices, BV_{DS} and BV_{DG} show a *negative* temperature coefficient. BV_{DS} increases from 7.9 V at 340K to 14.4 V at 220 K for x=0.53. This reveals that breakdown can not simply be due to impact-ionization in the channel. In fact, we found that in all cases, breakdown occurs from drain to gate, *i.e.* gate breakdown limits the drain-source voltage of the device. We also found that breakdown is not triggered by electrons from the source, a fact which signifies the successful application of the surface-depleted cap strategy in preventing premature channel breakdown.

The gate current approaching breakdown was found to be weakly thermally activated at around 300 K. The activation energy (E_A) for x=0.53 was 0.2 eV for low V_{DG}, and dropped to 0.09 eV at V_{DG}= 10 V. This is much lower than the Schottky-barrier height (0.7 eV) of InAlAs, indicating that there is a large electron tunnelling component through the triangular insulator barrier. For a given V_{DG}, higher x results in larger I_G and slightly lower E_A. For V_{DG}=4 V, E_A was 0.16, 0.09 and 0.06 eV for x=0.53, 0.62, and 0.70 respectively.

The simultaneous occurrence of impact-ionization was established by directly detecting holes with a negatively biased probe tip used as a sidegate. The Drain-current Injection technique at I_D=1 and 1.5 mA/mm was used. The sidegate current, I_{SG}, was found to correlate with I_G. Also, larger I_D resulted in increased I_{SG} . The verification of impact-ionization in the breakdown process suggests that the lower BV of InAs-rich channels arises from enhanced impact-ionization due to their smaller channel bandgap.

Our findings suggest that there is considerable room for breakdown voltage engineering [2] in InAlAs/InGaAs MODFETs by the use of a higher-barrier low-InAs insulator, a thicker undoped barrier-layer, and enhancement of the channel bandgap by quantum-confinement.

[1] J. Dickmann *et al.* Electronics Lett. **28**, 1849, 1992. [2] S. R. Bahl *et al.* IEEE Electron Dev. Lett. **14**, 22, 1993.

thickness	doping	material
200 A	6.0E18 cm^{-3} exponential 5.0E17	InGaAs
200 A	--	InAlAs
30 A	8.0E18	InAlAs
20 A	--	InAlAs
400 A	--	InGaAs
40 A	--	InAlAs
40 A	--	InGaAs
2500 A	--	InAlAs
40 A	--	InGaAs
40 A	--	InAlAs

Semi-insulating InP

Fig. 1: Schematic of device heterostructure.

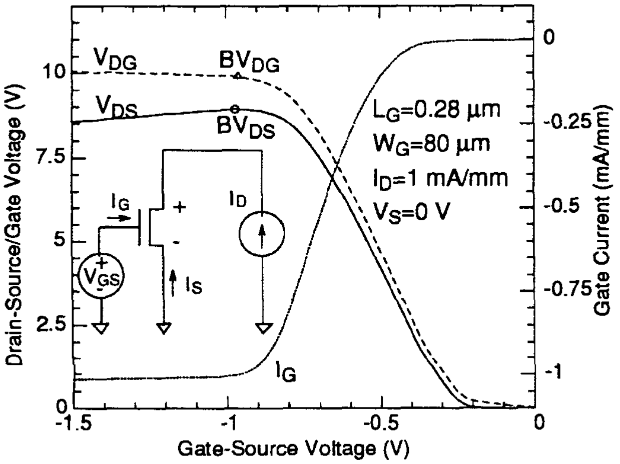

Fig. 3: The Drain-current Injection technique.

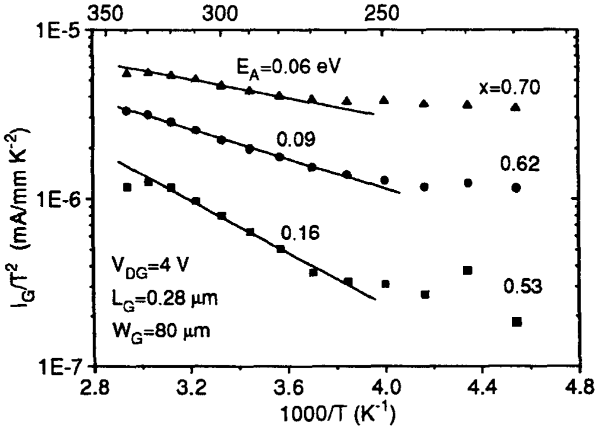

Fig. 5: Activation energies at V_{DG}=4 V.

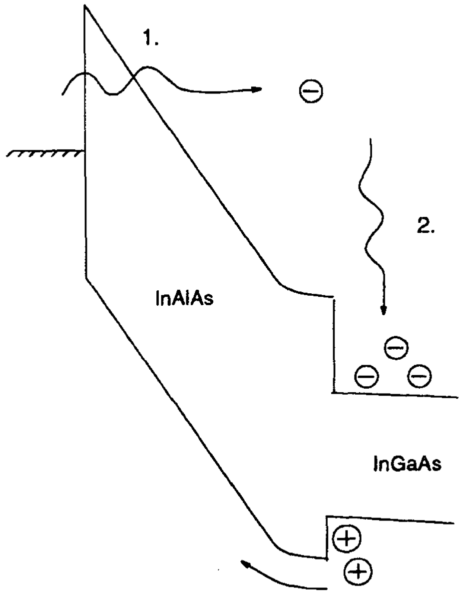

Fig. 2: The Thermionic-emission/impact-ionization process

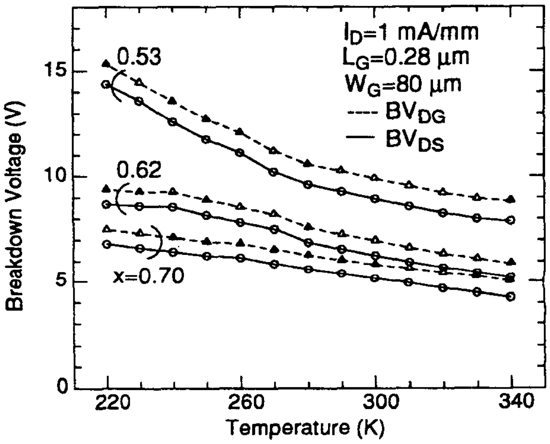

Fig. 4: Breakdown voltages vs. temperature

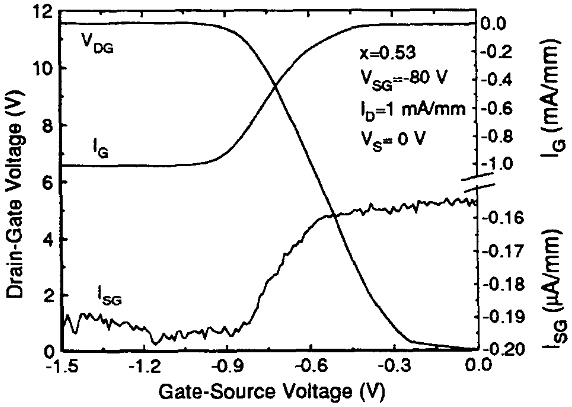

Fig. 6: Detection of holes by the sidegate