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Indium Content Dependence of Electron Velocity and Impact Ionization in InAlAs/InGaAs Metamorphic HEMTs

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1. Introduction

Metamorphic InGaAs devices grown on GaAs substrates, such as metamorphic high electron mobility transistors (MHEMTs) and metamorphic hetero bipolar transistors (MHBTs), are attractive candidates for micro- and milli-meter wave low noise and power applications. A benefit of the metamorphic devices is the degree of freedom given by the range of Indium content. High-frequency performance and breakdown voltage can be balanced by chosing Indium content in device optimization. It has been shown that, with reduction of Indium content, current gain cut-off frequency decreases and Schottky breakdown voltage, which governs off-state breakdown voltage, increases using 0.1 μm gate length InAlAs/InGaAs MHEMTs [1].

In the present work, using $In_xAl_{1-x}As/In_xGa_{1-x}As$ MHEMTs, we have carried out a systematic study on the electron velocity in InGaAs channel, which is obtained from gate length dependence of the cut-off frequency. Moreover, impact ionization phenomena in InGaAs channel, which dominates *on-state* breakdown voltage, have been investigated. The experiments were performed by MHEMTs with x=0.36, 0.43, 0.52, and lattice matched HEMTs (LMHEMTs, x=0.53) grown on an InP substrate to compare with MHEMTs.

2. Materials and Device Fabrications

The MHEMT structures were grown by molecular beam epitaxy on (001) semi-insulating GaAs substrates. The graded InAlAs buffers [2] were grown to accommodate the lattice-mismatch strain between GaAs and InAlAs/InGaAs. A cross section of the heterostructures is shown in Fig.1. The active layer of LMHEMTs is the same structure. Indium content of InGaAs channel, dislocation density, and Hall measurement results after recess etching are summarized in Table I. The Indium contents were precisely determined by photoluminescence measurements taking into account quantized energy levels in the channels, and (004) and (115) X-ray diffraction measurements. Dislocation density of each MHEMTs measured by plain-view transmission electron microscopy was about 10^8 cm^{-2}, which is larger than that of LMHEMTs by three orders of magnitude. Nevertheless, high electron mobility were obtained for MHEMTs. This indicates that dislocation does not affect the electron velocity at low electric fields.

The device fabrication was started with isolation by wet etching. The T-gate structures with gate length of 0.12–1.0 μm were realized by tri-layer resist process with electron-beam lithography. The gate length was precisely measured by critical dimension scanning electron microscopy. The selective wet recess etching was performed using mixture of adipic acid, ammonia and hydrogen peroxide [3]. After the recess etching, Pt/Ti/Pt/Au was deposited and lifted-off for the gate. Then alloyed Ni/AuGe/Au ohmic contacts were formed. Typically, the ohmic contact resistance was 0.2, 0.3, and 0.35 Ωmm for x=0.52, 0.43, and 0.36, respectively. Finally, Ti/Au contact pads were formed.

3. Experiments and Analysis

Current gain cut-off frequency f_T for MHEMTs and LMHEMTs as a function of gate length L_g is shown in Fig.2, which was obtained by the S-parameter measurements at optimum bias conditions. MHEMTs with x=0.52 and LMHEMTs exhibit the same L_g dependence of f_T. This indicates that dislocation in MHEMTs does not affect the electron velocity at high electric fields. In the range of 0.4 μm$<L_g<$1.0 μm, $L_g \times f_T$ of 33, 30, and 23 GHz·μm are obtained for x=0.52, 0.43, and 0.36, respectively. The average electron velocity v_{ave} of InGaAs calculated by the relation $f_T = v_{ave}/2\pi L_g$ are 2.1×10^7, 1.9×10^7, and 1.5×10^7 cm/s for x=0.52, 0.43, and 0.36, respectively.

Impact ionization phenomena were studied by the method proposed in [4]. According to the method, the impact ionization rate is proportional to

$$I_g/(I_d L_{eff}) = A\exp(-E_i L_{eff}/(V_d - V_{sat})),$$

where I_g is gate current, I_d is drain current, V_d is drain voltage, V_{sat} is the saturation voltage, L_{eff} is the effective length of the high electric field region, A is constant, and E_i is the characteristic electric field of impact ionization. Figure 3 shows $\ln(I_g/I_d)$ as a function of $1/(V_d - V_{sat})$ for 1.0 μm gate length HEMTs. Gate voltage was set 0.3 V above the threshold voltage in the measurements.

The curves of LMHEMTs and MHEMTs with x=0.52 converge to the same line. This indicates that crystalline defects of MHEMTs do not influence impact ionization phenomena. Since E_i of InGaAs for LMHEMTs is 9.0×10^5 V/cm, which was obtained by photocurrent gain measurements [5], we can determine that L_{eff} is ~420nm, which is shorter than gate recess side etching length of 580nm. In the analysis of MHEMTs, it is plausible that L_{eff} of MHEMTs is assumed to be equal to that of LMHEMTs because all HEMTs have the same device structure. Under this assumption, E_i of 9×10^5 V/cm for x=0.52 and 0.43, and 2.1×10^6 V/cm for x=0.36 are obtained at electric field $\sim 2.5 \times 10^5$ V/cm.

Indium content dependence of v_{ave} and E_i are summarized in Fig.4. The values of v_{ave} and E_i of x=0 are referred to [4] and [6], respectively. With reduction of Indium content, v_{ave} decrease. Although E_i for x=0.52 and 0.43 are same, that for x=0.36 increases significantly.

4. Summary

Using InGaAs/InAlAs HEMTs, we have investigated gate length dependence of current gain cut-off frequency. As a result, we have found the average electron velocity v_{ave} in InGaAs with several Indium contents. Furthermore, impact ionization phenomena have been studied. The Indium content dependence of the characteristic electric field of impact ionization E_i is obtained. We have observed no difference between MHEMTs with x=0.52 and LMHEMTs, despite the existence of dislocation in MHEMTs. Since E_i increases significantly for x=0.36, high on-state breakdown voltage is obtained with Indium content $\lesssim 0.4$.

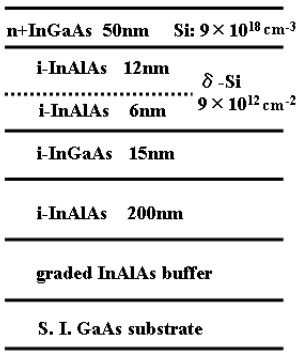

Fig.1. A cross section of MHEMT structures.

Table I. Indium content of InGaAs channel x, dislocation density D, room temperature Hall mobility μ and sheet carrier density n_s of LMHEMTs and MHEMTs.

x	0.53(LM)	0.52	0.43	0.36
D [cm^{-2}]	$< 10^5$	3.5×10^8	3.0×10^8	8.0×10^7
μ [cm^2/Vs]	10000	10200	9800	8400
n_s [10^{12}cm^{-2}]	3.5	3.9	3.8	3.3

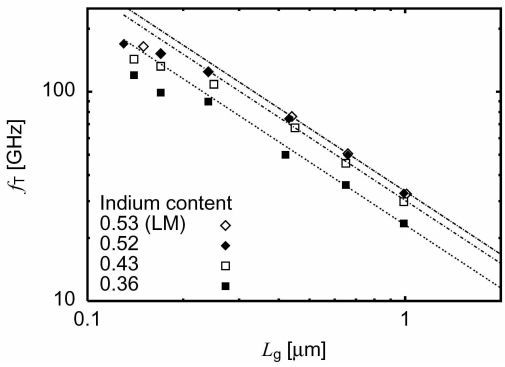

Fig.2. Cut-off frequency f_T as a function of gate length L_g for LMHEMTs and MHEMTs.

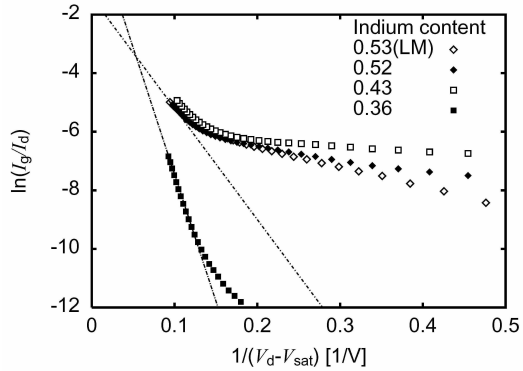

Fig.3. $\ln(I_g/I_d)$ as a function of $1/(V_d - V_{sat})$ for 1.0 μm HEMTs. I_g: gate current, I_d: drain current, V_d: drain voltage, and V_{sat}: saturation voltage.

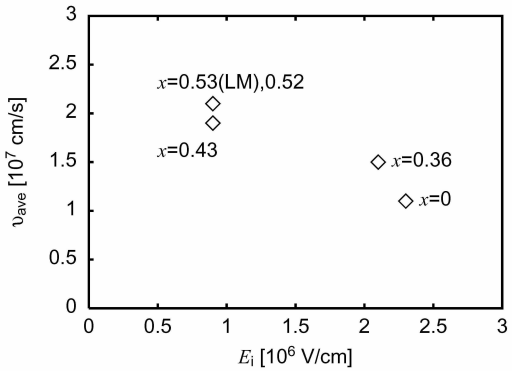

Fig.4. The average electron velocity v_{ave} and the characteristic electric field of impact ionization E_i for InGaAs with several Indium contents x.

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