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Electron Transport and Microwave Noise in MBE- and MOCVD-Grown AlGaN/AlN/GaN

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Microwave noise temperature, current, and dissipated power were investigated at room temperature in undoped AlGaN/AlN/GaN channels grown by molecular beam epitaxy and metal-organic compound vapour decomposition techniques. Samples with essentially the same electron density ($1 \times 10^{13} \text{ cm}^{-2}$) and low-field mobility ($1150 \text{ cm}^2/(\text{V s})$) demonstrated considerably different behaviour at high electric fields. The effective hot-phonon lifetime, 300 fs and 1000 fs, respectively, was estimated for molecular beam epitaxy and metal-organic compound vapour decomposition samples. The expected anti-correlation of hot-phonon lifetime and hot-electron drift velocity was confirmed experimentally.

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1. Introduction

A two-dimensional electron gas channel of a nitride high-electron-mobility transistor (HEMT) supports excellent microwave-power generation at 10 GHz frequency [1]. The power at centimetre waves has increased from (5–10) W/mm in year 2000 up to 30 W/mm in 2004 [2]. However, advances in nitride HEMT technology did not lead to an improvement of transistor operation at millimeter-wave frequencies: the best result on cut-off frequency, 121 GHz, remained neither repeated nor exceeded since 2002 [3]. An essentially better performance at mm-waves is expected from the electron drift velocity measured [4] for a low-electron-density GaN pin diodes and calculated [5] for a two-dimensional AlGaN/GaN channel

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with hot phonons ignored. However, hot phonons are known to reduce the electron drift velocity [6]. The calculated drift velocity is higher if hot-phonon lifetime is shorter [7] and the electron three-dimensional density is lower [8]. This paper aims to confirm experimentally the expected anti-correlation of the electron drift velocity and the hot-phonon lifetime.

2. Background

The hot-phonon lifetime can be estimated from experimental dependence of dissipated power on noise temperature [7, 9]. Under a steady state, the dissipated power per electron P_d equals the supplied power P_s :

$$P_d = P_s = UI/N_e, \quad (1)$$

where I is the current, U is the voltage, and N_e is the electron number in the channel.

The microwave noise temperature T_n nearly equals the electron temperature T_e in a wide range of fields supposing that other noise sources are weak [9, 10]. Thus, in the electron temperature approximation, for dominant interaction of hot electrons with longitudinal optical (LO) phonons under the condition $T_n \cong T_e$, the dissipated power can be expressed as [9]

$$P_d = (\hbar\omega/\tau_{ph})\{\exp(\hbar\omega/k_B T_n) - 1\}^{-1} - \exp(\hbar\omega/k_B T_0) - 1\}^{-1}, \quad (2)$$

where $\hbar\omega$ is the LO phonon energy, T_0 is the equilibrium temperature, and k_B is the Boltzmann constant. The fitting parameter τ_{ph} is the effective LO-phonon lifetime.

3. Samples

Undoped AlGa_{0.2}N/AlN/GaN structures were grown by molecular beam epitaxy (MBE) and metal-organic compound vapour decomposition (MOCVD) techniques. A two-dimensional electron gas channel is formed in GaN layer due to polarisation and piezoelectric fields. The structures with essentially the same sheet electron density ($1 \times 10^{13} \text{ cm}^{-2}$) and low-field mobility ($1150 \text{ cm}^2/(\text{V s})$) were selected for current, dissipated power, and microwave noise temperature measurements. The AlN layer thickness was 1.5 nm and 2 nm, respectively, in MBE and MOCVD structures; this thickness was sufficient to avoid hot-electron penetration into AlGa_{0.2}N layer and the associated noise [9]. Experiments were carried out on samples with two coplanar ohmic electrodes ($100 \times 100 \text{ nm}^2$) separated with 5 μm gaps. Strong electric field was applied in the plane of the two-dimensional channel. The noise temperature was measured near 10 GHz in the range of field where interaction of hot electrons with longitudinal optical phonons is the dominant scattering mechanism and the electron temperature nearly equals the noise temperature [9].

4. Experimental results and discussion

Figure 1 illustrates dependence of current on electric field. The self-heating effects are avoided in the field range below 100 kV/cm when the voltage pulse duration is $t_p = 150$ ns [10]. Low-field data are taken for $t_p = 2$ μ s; they show that the current is almost the same in the investigated MBE and MOCVD samples (Fig. 1, circles and triangles). Consequently, the electron drift velocity is nearly the same at low fields. However, at high fields, the drift velocity is lower in the MOCVD sample (Fig. 1, triangles) as compared with the MBE one (circles). The saturated electron drift velocity, estimated from the experimental data on the current, the sheet electron density, and the channel width, is 1.1×10^7 cm/s in the MBE-grown AlGaIn/AlN/GaN [10].

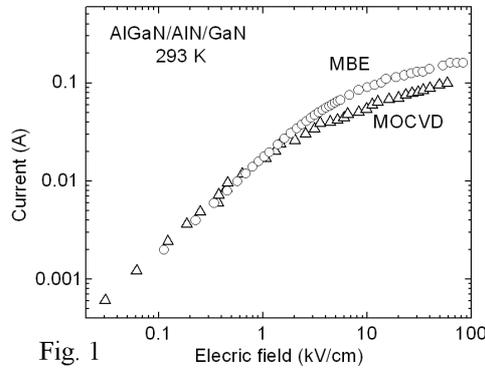


Fig. 1

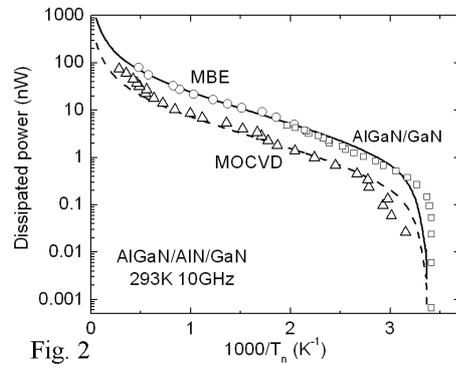


Fig. 2

Fig. 1. Dependence of current on electric field at 300 K for AlGaIn/AlN/GaN: MOCVD (triangles) and MBE (circles).

Fig. 2. Dissipated power against reciprocal noise temperature for AlGaIn/AlN/GaN (symbols): MOCVD (triangles), MBE (circles). Squares are for AlGaIn/GaN [7], lines stand for Eq. (2): $\tau_{ph} = 300$ fs (solid line) and $\tau_{ph} = 1000$ fs (dashes).

The measured dependence of the dissipated power on the reciprocal noise temperature (Fig. 2, symbols) is fitted with the semi-empiric expression (2). The experimental data agree with the curves plotted for the following fitting constant: $\tau_{ph} = 300$ fs (solid line) and $\tau_{ph} = 1000$ fs (dashes).

The comparison of the experimental data of Fig. 2 (symbols) and Eq. (2) (lines) shows that the effective LO-phonon lifetime is longer in the MOCVD-grown AlGaIn/AlN/GaN channel as compared with the MBE-grown one. It is evident that, at a given supplied power, the number of accumulated hot phonons is proportional to their lifetime. Therefore, a weaker hot-phonon effect is expected in the MBE sample.

Monte Carlo simulation with hot phonons taken into account predicts higher values of the hot-electron drift velocity at high electric fields for the channels with a shorter hot-phonon lifetime [7]. The experiment (Fig. 1) seems to confirm the

expectations: at a high electric field, the drift velocity shows a higher value in the MBE-grown channel as compared with the MOCVD-grown channel. Since the low-field properties are similar, the difference in the drift velocity at high electric fields is determined by the electron interaction with hot phonons rather than by other scattering mechanisms.

In summary hot-phonon lifetime is found to differ in AlGa_N/AlN/GaN two-dimensional channels grown by MBE and MOCVD techniques. The expected dependence of the hot-electron drift velocity on the hot-phonon lifetime is confirmed experimentally.

Acknowledgments

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