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Hot-Electron Transport and Microwave Noise in 4H–SiC

L. Ardaravičius*, J. Liberis, O. Kiprijanovič,
I. Matulionienė and A. Matulionis

Semiconductor Physics Institute, A. Goštauto 11, Vilnius 01108, Lithuania

Hot-electron transport and microwave noise are investigated for n-type 4H–SiC ($n = 2 \times 10^{17}$ cm^{-3}) subjected to a pulsed electric field applied parallel to the basal plane. At room temperature, the negative differential conductance, masked by field ionization at the highest fields, is observed in the field range between 280 and 350 kV/cm. The threshold fields for the negative differential conductance and field ionization increase with lattice temperature. The results on microwave noise are used to evaluate the effective hot-electron temperature and the hot-electron energy relaxation time.

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1. Introduction

Silicon carbide is a wide bandgap semiconductor used in high-power and high-temperature optical and microwave applications [1, 2]. Hot-electron properties in 4H–SiC have been studied at high electric fields applied parallel to the basal plane [3, 4]. Channel self-heating limits the highest fields in the experimental investigations unless nanosecond voltage pulses are used [5]. This paper presents the results on the steady-state hot-electron drift velocity and hot-electron noise measurements for n-doped 4H–SiC channel carried out under controlled self-heating.

2. Investigated structures and measuring techniques

The experiments were carried out on passivated donor-doped 4H–SiC two-electrode samples processed together with field-effect transistors. The wafer consisted of a semi-insulating 4H–SiC substrate, a p-type buffer layer (5×10^{15} cm^{-3}), and an n-type channel. The effective channel thickness (0.175 μm) and the electron density ($n = 2 \times 10^{17}$ cm^{-3}) were estimated from capacitance–voltage measurements. The low-field electron mobility was ~ 300 cm^2/(V s) which is similar to mobility reported in Ref. [6].

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[*] corresponding author; e-mail: linas@pfi.lt

Nanosecond pulses were formed by a mercury-wetted relay. A coaxial line was discharged through the relay, the electric pulse reached the sample, and the transmitted signal was fed into a 0–5 GHz bandwidth sampling oscilloscope [5]. The average applied electric field E in the channel was estimated according to $E = (V - IR_\mathrm{c})/L$, where V is the applied voltage, I is the current, R_c is the contact resistance, and L is the channel length.

High frequency noise power $P_{n\|}$ was measured at a 10 GHz frequency with the gated modulation-type radiometer [7]; the pulsed electric field was applied parallel to the basal plane, and the noise was measured in the field direction. For the matched impedances, the equivalent hot-electron noise temperature $T_{n\|}$ is:

$$T_{n\|} = P_{n\|}/(k_\mathrm{B}\Delta f), \tag{1}$$

where k_B is the Boltzmann constant, and Δf is the frequency bandwidth.

3. Experimental results

Figure 1 illustrates the current–field characteristics measured at pulse durations of 300 ns and 1 ns. The current changes less than 10% when the Joule heat increases 300 times. The heat at 50 kV/cm for 300 ns pulses (triangles) is higher as compared with that at the highest field for 1 ns pulses (circles), and we think that channel self-heating can be ignored in our experiments.

Two high-field effects are evident at high electric fields: (i) the negative differential conductance (NDC) is observed in the range from 280 to 350 kV/cm (Fig. 1, inset), (ii) the field ionization takes place at $E > 350$ kV/cm. The NDC is better resolved at elevated lattice temperatures (Fig. 2, squares and bullets). The field ionization threshold is much lower as compared with that in IMPATT

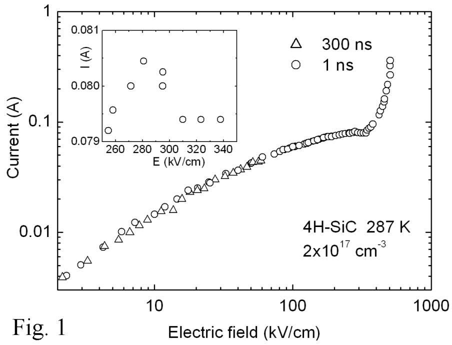

Fig. 1

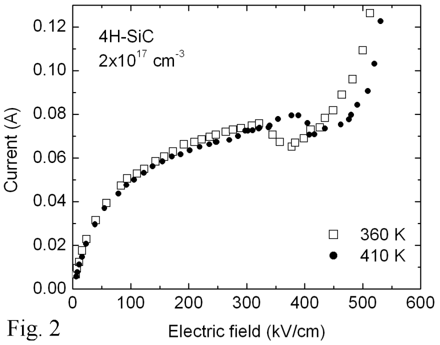

Fig. 2

Fig. 1. Dependence of current on electric field at 287 K at voltage-pulse duration: 300 ns (triangles) and 1 ns (circles). NDC is resolved in the inset. Electron density $n = 2 \times 10^{17}$ cm^{-3}, mobility $\mu_0 = 300$ cm^2/(V s). Channel dimensions (in microns): $0.175 \times 4 \times 100$.

Fig. 2. Dependence of current on electric field at 360 K (squares) and 410 K (bullets). Voltage-pulse duration — 1 ns.

diodes [8]; this suggests that the NDC might support the formation of high-field domains [5].

Data of Fig. 1 were used to estimate the dependence of the drift velocity on electric field according to the expression $v_d = I/enS$, which is valid at fields below the threshold for NDC where the electric field is expected to be uniform and the electron density n is independent of the electric field (here e is the elementary charge, S is the channel cross-section area). The dependence of v_d on lattice temperature is weak as seen from Fig. 2. The maximum value is 1.4×10^7 cm/s at room temperature.

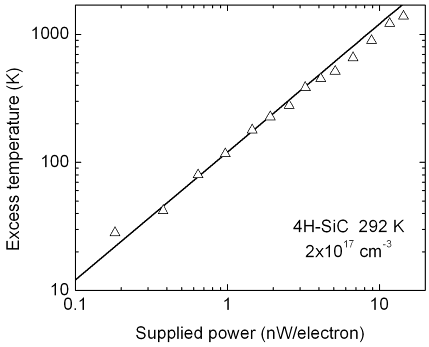

Fig. 3. Measured excess noise temperature against supplied power per electron at 292 K (triangles). Line is the calculation after Eq. (3), $\tau_\varepsilon = 2.5$ ps. Voltage-pulse duration is 300 ns.

The measured noise temperature $T_{n\parallel}$ is plotted in Fig. 3 (triangles) as a function of supplied power per electron $P_{\mathrm{s}} = UI/N_{\mathrm{e}}$, where N_{e} is the electron number in the channel, $U = V - IR_{\mathrm{c}}$ is the voltage drop along the channel. A nearly linear dependence is obtained at low/moderate bias. This behavior can be treated in terms of electron temperature [7, 9].

4. Discussion

The experimental results will be treated in terms of hot-electron temperature T_{e} which, strictly speaking, can be introduced at high electron densities [10]. In general, the longitudinal noise temperature $T_{n\parallel}$ exceeds the electron temperature [9, 10]:

$$T_{n\parallel} = T_{\mathrm{e}}[1 + c(T_{\mathrm{e}})]. \tag{2}$$

The extra term $c(T_{\mathrm{e}})$, caused by electron temperature fluctuations, vanishes if the current–voltage characteristic is linear [10]. In 4H–SiC, the deviations from Ohm's law are not large in the field range below 50 kV/cm (Fig. 1), and $c(T_{\mathrm{e}})$ remains below 20%. Thus, we shall assume $T_{n\parallel} \cong T_{\mathrm{e}}$. Then the obtained dependence of the electron temperature on the supplied power P_{s} can be treated in terms of hot-electron energy relaxation time τ_ε [9]

$$T_{\rm e} = T_0 + 2P_{\rm s}\tau_\varepsilon/(3k_{\rm B}). \tag{3}$$

The experimental results of Fig. 3 are fitted with Eq. (3) at $\tau_\varepsilon = 2.5$ ps (solid line).

The hot-electron energy relaxation is a many-step process in a biased n-type 4H–SiC channel: high-energy electrons launch longitudinal optical (LO) phonons, the latter are either reabsorbed by the electrons or decay into acoustic phonons, which drain the Joule heat out of the channel. The LO-phonon launch time ($\sim$ 10 fs) is much shorter as compared with the obtained hot-electron energy relaxation time ($\tau_\varepsilon = 2.5$ ps). The heat drain is efficient because of high thermal conductance of 4H–SiC, this process does not limit the electron energy dissipation. Discussion of similar results in nitride channels has shown that the electrons and the launched LO phonons form a fairly isolated non-equilibrium subsystem [11]. Because of weak coupling with the thermal bath and intense energy exchange in the subsystem, the hot electrons, and the launched LO phonons acquire the same temperature, and, at high electric fields, the electron energy relaxation time tends to the LO-phonon lifetime determined by the LO-phonon conversion into acoustic phonons [12]. Supposing that the same approach is applicable to 4H–SiC channels, the measured hot-electron energy relaxation time can be used as an estimate of the LO-phonon lifetime.

5. Summary

Nanosecond-pulsed techniques for current and microwave noise measurement were applied to study hot-electron transport and energy dissipation in 4H–SiC at high electric fields. The effects of NDC and field ionization were resolved, the threshold fields for these effects are found to increase with the lattice temperature. The hot-electron energy relaxation time at low/moderate fields, and the maximum drift velocity at high fields are estimated.

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