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RELAXATION OF CONDUCTIVITY IN AlGaN / AlN / GaN TWO-DIMENSIONAL ELECTRON GAS AT HIGH ELECTRIC FIELDS [*]

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AlGaN / AlN / GaN heterostucture with a very thin (0.6 nm) AlN spacer was investigated by conductivity relaxation measurements after a strong electric field action. To obtain the two-dimensional electron gas (2DEG) channel transport properties at high electric fields the relaxation results were extrapolated to the time of the peak of an applied nanosecond high-voltage electric pulse. Significant decrease of hot electron sheet density at high electric fields was revealed. The measured sample conductivity relaxation is decided not only by the changes of 2DEG channel conductivity due to variation of sheet density. This does not allow one to obtain corrected drift velocity values at high electric fields. The obtained results show that the AlN thickness must be more than 0.6 nm.

Keywords: nitride heterostructures, two-dimensional electron gas, hot electrons, AlGaN / AlN / GaN

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1. Introduction

Microwave performance of high electron mobility transistors (HEMTs) is mainly decided by electron transport along the two-dimensional electron gas (2DEG) channel [1]. Nitride heterostructure channels show great potential for high-power and high- temperature operation [2, 3]. The investigation of 2DEG transport is important for the HEMT performance improvement for application, especially at high electric fields. Drift velocity as the transport parameter can simply be evaluated from results of current and electron density when electric field is homogeneous and impact ionization or hot-electron capture are absent. Hot electron trapping reduces free electron density in the 2DEG channel. Due to this, the evaluation of the electron drift velocity should be reconsidered.

Relaxation methods are used to investigate properties of semiconductors such as conductance, free carrier density, lifetime of non-equilibrium carriers, etc. The hot-electron capture in AlGaN / AlN / GaN was revealed at electric field exceeding 25 kV/cm in nanosecond time scale [4]. The results were discussed without assuming the barrier form changed. However, hot electrons may be injected through AlN barrier into AlGaN at high electric fields. The relaxation method may be used for the investigation of AlN potential barrier properties. The piezoelectric polarization of AlGaN on GaN is determined by the strain in AlGaN layer and the polarization is strongly influenced by elastic strain relaxation of the layer. Therefore an ultrathin AlN spacer is sensitive to applied high electric field.

In this work the relaxation technique was used for investigation of the barrier properties modified by strong electric field applied to the channel and for evaluation of the free electron drift velocity. Relaxation of 2DEG conductance after applying nanosecond high electric field pulses was measured at low fields. The 2DEG channel was located in an AlGaN / AlN / GaN heterostructure with an ultrathin (0.6 nm) AlN spacer.

2. Sample characterization

The relaxation of the low-field resistance was studied for AlGaN / AlN / GaN heterostructures grown by MOCVD at the University of California (Santa Barbara). The wurtzite group III nitrides, GaN and AlN, are tetrahedrally coordinated semiconductors; a hexagonal Bravais lattice contains four atoms per unit cell. For binary compounds with wurtzite structure, the

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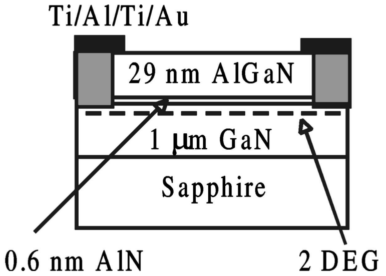

Fig. 1. Schematic diagram of an AlGaN / AlN / GaN heterostructure.

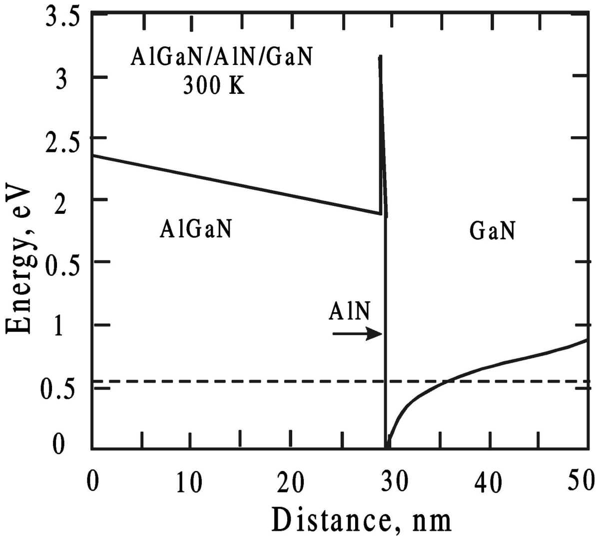

Fig. 2. Schematic conduction band profile (solid line). Dotted line is the Fermi energy.

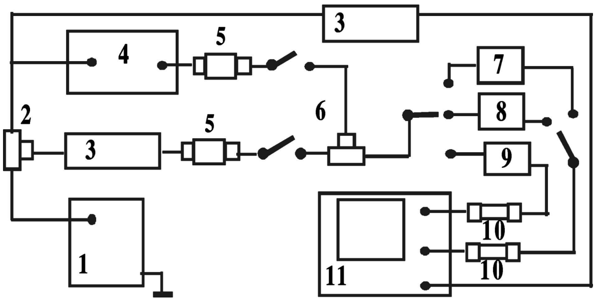

Fig. 3. Circuit of the experimental set-up for measurements at high and low electric fields in nanosecond time scale. *1* is nanosecond pulse generator, *2* is synchronization tee, *3* delay line, *4* test pulse generator, *5* power attenuator, *6* non-matched tee, *7* low field gauge resistor, *8* high field gauge resistor, *9* sample, *10* broadband attenuator, *11* two channel sampling memorized oscilloscope.

sequence of atomic layers of the two constituents is reversed along the c axis. The investigated structures are chosen to be Ga-face with c axis taken to be perpendicular to the heterointerfaces. For crystals with Ga-face polarity one bilayer consists of a metal layer above the nitrogen layer. The piezoelectric and spontaneous polarizations point in the same direction; this increases the difference in the values of the overall polarization of the heterostructure layers. The spatial gradient of the polarization at an abrupt interface between the top and the bottom layers induces a fixed charge density. The resultant fixed polarization-induced charge is positive, and free electrons tend to compensate it. Thus, the fields induced by spontaneous and piezoelectric polarization were responsible for the 2DEG formation [5]. Recently, there has been proposed an AlN (1.5 nm) + GaN (4 nm) spacer [6] which reduces the hot-electron scattering by the AlGaN alloy; the scattering is supposed to be present in AlGaN / GaN device. This results in 20% increase of hot electron drift velocity compared with the AlGaN / GaN device. By a combination of Hall effect and C–V profiling measurements, the interface at which the carriers are accumulated and the sign of the carriers were identified at the University of California, Santa Barbara. The investigated ultrathin channel had electron sheet density $n_0 = 9.78 \cdot 10^{12}$ cm^{-2} and mobility $\mu = 1664$ cm^2/(V·s). The composition and layer thickness are schematically shown in Fig. 1. Sample width w equals to 90 μm. Coplanar Ti / Al / Ti / Au electrodes were formed at 1080 K; two 100×100 μm^2 contact pads were separated with a gap $d = 12$ μm. The schematic conduction band potential profile of the AlGaN / AlN / GaN heterostructure channel is drawn in Fig. 2. The profile was considered to be similar to that calculated for the same type heterostructure [7]. A strong (of the order of tens of kv/cm) electric field parallel to the heterointerfaces was applied to the samples. A thin undoped layer – AlN spacer prevents electrons to be injected into AlGaN and reduces electron alloy-disorder scattering. Therefore it increases 2DEG sheet density and mobility. Electrons are heated after they are injected into the channel. Monte Carlo results show that the electrons obey Fermi–Dirac distribution with an electron temperature entering as a parameter. The electron temperature depends on electric field and can be evaluated from noise measurements. For example, the electron temperature for the investigated AlGaN / AlN / GaN sample equals to 620 K at an electric field of 28 kV/cm.

3. Experimental set-up

Current–voltage and low-field resistance relaxation measurements in nanosecond time scale were performed using combined experimental set-up. Schematic diagram of the set-up is presented in Fig. 3.

The low-field part of the set-up contains the test generator (*4*) that provides relatively long (500 ns) low-

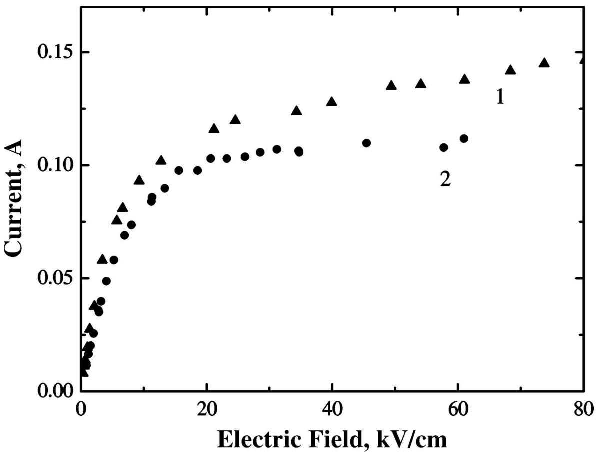

Fig. 4. Current–voltage dependences of the AlGaN / AlN / GaN samples: *1* for the sample at the beginning of measurements, *2* for the sample after the soft degradation.

voltage pulse for relaxation measurements; the pulse amplitude is lowered by tee (*6*). Resistance of a gauge resistor (*7*) has a value close to the sample resistance; the resistor *7* is used for measurement of low-voltage pulse incident amplitude. The high-field part of the set-up consists of a mercury-wetted relay generator (*1*) with a charged line and a dc source, a variable power attenuator (*5*) that is used for high pulse amplitude control, a gauge resistor (*8*) with resistance higher than the sample resistance. The gauge resistor *8* is used to measure the incident high-voltage pulse amplitude fed to the oscilloscope (*11*) first input. Thin film attenuators (*10*) serve as the oscilloscope input protectors. Useful information is obtained from the measurement when pulses are transmitted through the sample.

4. Results

Figure 4 presents the current I as a function of the average estimated electric field $E = (V - IR_c)/d$, where V is the applied voltage and R_c is the contact resistance. Curve *1* demonstrates the dependence for the sample at the beginning of experiments. Curve *2* demonstrates the dependence for the sample subjected to the fields above 50 kV/cm for many times; channel degradation is observed.

Table 1. Approximation parameters entering into formula (1).

	A_1	τ_1, ns	A_2	τ_2, ns	$\sigma(0)$, S
$E = 42$ kV/cm	1	12	0	–	0.013
$E = 49$ kV/cm	0.9	10	0.1	18	0.009
$E = 59$ kV/cm	0.78	7	0.22	18	0.005
$E = 71$ kV/cm	0.75	6	0.25	18	0.002

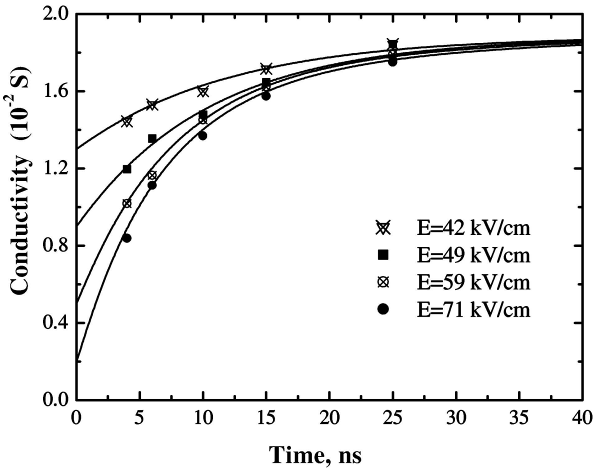

Fig. 5. Low-field conductivity relaxation of the sample after the high pulse action. Symbols show experiment, lines represent exponential approximation (1).

Low-field conductivity relaxation for several high electric field values is presented in Fig. 5 by symbols. One can see that if the higher field is applied to the sample then the conductivity of the sample becomes lower when the field is off. The results, approximated with exponential components by a formula

$$\sigma(t) = [\sigma_0 - \sigma(0)]\left\{A_1\left[1 - \exp\left(-\frac{t}{\tau_1}\right)\right] + A_2\left[1 - \exp\left(-\frac{t}{\tau_2}\right)\right]\right\} + \sigma(0) \quad (1)$$

and extrapolated to zero time conductivity $\sigma(0)$, are presented as lines in Fig. 5. Results of approximation and $\sigma(0)$ values are shown in Table 1; σ_0 is the sample conductivity; it is equal to 0.019 S.

Figure 5 and data of Table 1 show that the relaxation process at high electric fields consists of two parts. One part has a lower amplitude A_2 and time constant τ_2 of about 18 ns; another part has a smaller time constant τ_1 decreasing from 12 to 6 ns and higher amplitude A_1. Additionally there was observed a very long (lasting from 1 hour to several days) relaxation process during which the sample resistance goes down by 4–6% back to the normal resistance. This relaxation appears after high voltage electric pulses (above 50 kV/cm).

5. Discussion

The process with a greater time constant (18 ns) we assign to hot electron capture in the GaN layer followed by electron thermal release in the same way as discussed for samples with a 1.5 nm thick AlN barrier, observed in the field range from 25 to 30 kV/cm [4].

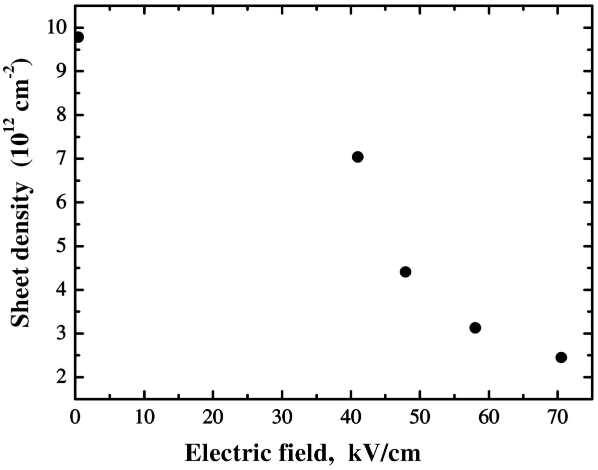

Fig. 6. Sheet electron gas density of the sample versus electric field strength.

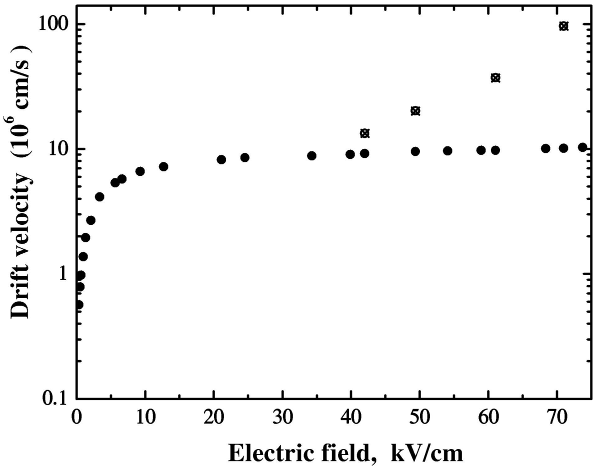

Fig. 7. Electron drift velocity versus electric field strength. Filled circles when assuming constant n_0, crossed circles under assumption of concentration decrease due to electron capture at higher fields.

We attribute the faster process to the possible influence of electric field on the shape of the barrier modified by hot electron injection and on the channel strain changing the piezoelectric polarization.

The 0.6 nm thick AlN layer does not prevent the hot electrons from tunnelling into the AlGaN layer at high electric fields. When the high electric field is off, the electrons return to 2DEG channel, but it takes time, if the carriers are captured by the centres located in AlGaN and at the heterojunction between AlN and AlGaN. Usually, the thickness of the spacer is less than 3 nm [6], but on the other hand the ultrathin spacer cannot be too thin because it has to prevent electrons from tunnelling and to decrease electron scattering induced by AlGaN barrier.

Also, a very long relaxation appears, which is attributed to piezoelectric polarization recovery [8] and channel degradation (Fig. 4 curve *2*) after multiple strong electric field action.

On the base of these assumptions let us derive the 2DEG channel transport properties under the action of a high electric field. Field dependent electron drift velocity is obtained using formula (2) assuming initial sheet concentration n_0:

$$v_{\mathrm{dr}} = \frac{I}{e\,n_0\,w}\,, \qquad (2)$$

see filled circles in Fig. 6, where e is the electron charge.

Further, as it follows from the low field measurements, $n(t)/n_0 = \sigma(t)/\sigma_0$. Using extrapolated data one can obtain $n(E)$ for measured electric field values at zero time, and put it in formula (2) instead of n_0. Crossed circles in Fig. 7 show corrected drift velocity at higher fields. One can see that obtained drift velocity values strongly exceed the maximum possible ones $v_{\mathrm{dr}} = 25{\cdot}10^6$ cm/s at 80 kV/cm in GaN [9]. This means that the measured sample conductivity relaxation is not only decided by the changes of 2DEG channel conductivity due to variation of sheet density. Therefore one cannot estimate 2DEG density from conductivity relaxation measurements and correct drift velocity values at high electric fields.

Most probably, since the AlN layer is thin (0.6 nm), after the threshold (25–30 kV/cm) [4] some part of 2D hot electrons become 3D in GaN and, additionally, in AlGaN as a result of big probability for very hot electrons to tunnel through the barrier. At electric fields exceeding 50 kV/cm, changes in piezoelectric polarization reduce channel conductivity, weaken the barrier properties and appearance of new traps in heterostructure is evident [10]. Sheet electron density and electron mobility decrease under these conditions. The recovery of the strained state and of the barrier properties after the nanosecond high pulse action as well as 3D electrons return into 2DEG are not so fast processes. It would be very interesting to continue measurements at lower temperatures because of significant 2DEG mobility increase.

6. Conclusions

AlGaN / AlN / GaN heterostructure with an ultrathin AlN barrier (0.6 nm) was investigated using relaxation method. It was found that at electric fields above 50 kV/cm the shape of barrier degrades due to changes in piezoelectric polarization. Hot electron scattering and number of traps increase under these conditions.

Part of two-dimensional electrons (not only due to tunnelling) became three-dimensional. Significant decrease of 2DEG sheet density at high electric fields was revealed. All this indicates that the AlN thickness must be higher than 0.6 nm.

Relaxation methods could be employed for analysis of AlN and other barriers properties in AlGaN / AlN / GaN heterostructures applying high electric fields of nanosecond duration, which is important for investigation hot electron transport in two-dimensional channels.

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AlGaN / AlN / GaN DVIMAČIŲ ELEKTRONŲ DUJŲ LAIDUMO RELAKSACIJA STIPRIUOSE ELEKTRINIUOSE LAUKUOSE

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Santrauka

AlGaN / AlN / GaN įvairialytis darinys, turintis labai ploną (0,6 nm) AlN tarpinį sluoksnį, buvo tirtas matuojant laidumo relaksaciją po stipraus elektrinio lauko impulso. Norint įvertinti dvimačių elektroninių dujų kanalo pernašos savybes, relaksacijos matavimo rezultatai buvo ekstrapoliuoti į lauko maksimumo momentą, kai buvo paleistas nanosekundinės trukmės aukštos įtampos elektrinis impulsas. Pastebėtas žymus karštųjų elektronų dvimačių elektronų dujų tankio sumažėjimas stipriame elektriniame lauke. Išmatuota bandinio laidumo relaksacija, vykstanti išjungus stiprų elektrinį lauką, nėra lemiama vien dvimačio kanalo laidumo kitimo, kintant jame elektronų tankiui. Iš šio laidumo kitimo negalime vertinti dvimačių elektroninių dujų tankio ir tokiu būdu patikslinti dreifo greičio stipriame elektriniame lauke. Siekiant pagerinti kanalo savybes, sluoksnio storis turi būti didesnis nei 0,6 nm.