Study of electrical properties of single GaN nanowires grown by molecular beam epitaxy

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Abstract. Electrical properties of single GaN nanowires grown by means of molecular beam epitaxy with N-plasma source were studied. Ohmic contacts connected to single n-type GaN wires were produced by the combination of electron beam lithography, metal vacuum evaporation and rapid thermal annealing technique. The optimal annealing temperature to produce ohmic contacts implemented in the form of Ti/Al/Ti/Au stack has been determined. By means of 2-terminal measurement wiring diagram the conductivity of single NW has been obtained for NWs with different growth parameters. The method of MESFET measurement circuit layout of single GaN nanowires (NWs) has been developed. In accordance with performed numerical calculation, free carriers’ concentration and mobility of single NWs could be independently estimated using MESFET structure.

1. Introduction

Semiconductor nitride compounds are very interesting for producing state-of-the-art high efficient semiconductor devices. Having a wide band gap (3.4 eV [1]) with relatively large electron affinity (about 4 eV [1]), GaN is a very promising semiconductor material for optoelectronic devices, in particular for solar cells.

One of the main challenges of 21st century is to develop low cost and high efficient renewable sources of energy including high efficient solar cell (SC). Nowadays the best results in this field have been achieved with tandem SC lattice-matched to GaAs substrate. It’s worth noting that the cost of such SC is very high. In order to reduce production costs cheaper Si wafers could be used. The main problem related to production of Si substrate based solar cell is the lack of lattice-matched materials with good opto-electronic properties. One of potential candidates for this purpose could be diluted nitride compounds [2] which are direct bandgap A3B5 semiconductors lattice-matched to Si substrate.

Another way is to use nanowire (NW) arrays as top SC junctions [3, 4]. Thus binary nitride materials (AlN, GaN, InN) could be grown on lattice-mismatched Si wafers without dislocations. These structures are very promising due to high crystal quality and excellent anti-reflection properties [5].
In order to achieve device high reproducibility it’s important to link the growth parameters with electrical and optical properties of synthesised NWs. In order to independently measure carrier concentration and mobility in thin films, the Hall method is used. But in case of property study of a single NWs, filed-effect transistor (FET) structure is more suitable [6].

2. Experiment

Using molecular beam epitaxy GaN NWs with different n-doping levels have been synthesized. On figure 1 one can see SEM image of GaN NWs array grown on Si substrate using Veeco GEN III MBE machine. The doping level was determined by the temperature value of the Si effusion cell. Two types of NWs samples were studied namely undoped GaN NWs and n-doped NWs with 1050°C temperature of the Si effusion cell. The NWs length of both sample types was about 1 μm. NWs diameter was in the range of (30-40) nm.

With ultrasonic treatment of NW submerged in isopropyl alcohol, the NWs were moved from their native growth Si wafer to the quartz substrate. Using combination of electron beam lithography and metal vacuum evaporation, contacts composed of Ti/Al/Ti/Au stack were attached to single NWs. After contacts formation the samples were annealed in rapid terminal annealing (RTA) machine at 630 – 850°C and 650-700°C for undoped and n-doped NWs, respectively. The ohmic linear behaviour for n-doped NWs was achieved after 7 minutes annealing at 700°C, but for undoped NWs the contacts remained non-ohmic under 800°C. At the temperature exceeding 850°C the contacts were broken. It should be mentioned that in case of non-ohmic behaviour, NWs conductivity could be reasonably well estimated at high voltage zone of volt-ampere characteristic (VAC).

The results of VAC study of both NWs samples in 2-terminal measurement wiring diagram (without gate contact) are indicated on figure 2. Insert on figure 2 (a) shows SEM image of single NW with two Ti/Al/Ti/Au contacts after annealing. Near linear behavior of VAC of both samples confirms the ohmic behavior of the contacts attached to single NWs. The main problem in producing ohmic contact to GaN is necessary to use Al which reacts with any of diffusion barriers as Ti, Ni, Ta, Mo. This leads to formation of intermetallic compounds and breaking the contacts.
According to obtained data, conductivity \( \sigma = e \cdot n \cdot \mu \) (where \( e \), \( n \) and \( \mu \) are electron charge, carrier concentration and carrier mobility) of undoped and doped NWs can be estimated to be 0.05 S/cm and 0.5 S/cm, respectively. Thus we can use 2-terminal measurement circuit layout only to obtain the multiplication of the two values \((n \cdot \mu)\), but not any of those values separately.

For independent evaluation of free carriers’ concentration and their mobility FET measurement circuit layout could be implemented. In case of FET structure the source and the drain terminals are connected to the semiconductor via ohmic contacts, the channel conductivity (channel width) is a function of the potential applied across the gate and the source terminals. Volume of depletion layer in semiconductor lying under gate contact is mostly determined by free carriers’ concentration rather than their mobility. In case of NW, metal-semiconductor FET (MESFET) measurement circuit layout is more suitable for \( n \) and \( \mu \) determination, where gate contact is formed by Schottky contact between NW and metal. For Schottky contact to n-doped GaN, metals with high value of work function, ex. Ni, Pd, Pt, could be used. Figure 3 shows technological process of NW structure fabrication in MESFET structure. Gate Schottky contact could be formed by Pd thermal evaporation.

Figure 2 (a, b). Volt-ampere characteristics of undoped (a) and n-doped (b) NWs collected with 2-terminals measurement circuit layout. Inset in (a) shows SEM image of single GaN NW with 2 ohmic Ti/Al/Ti/Au contacts.

Figure 3. Scheme of technological process of NW structure fabrication in MESFET measurement circuit layout.
3. Modeling

Numerical modeling was conducted to show the possibility of independent estimation of the carriers’ concentration and their mobility via studying volt-ampere curves obtained using MESFET structure. In our calculation values of NW conductivity and work function of gate metal were fixed, Pd was considered as a gate contact. Surface states at GaN NW surface and piezo effect contributions were not included in modeling.

Figure 4 shows set of calculated volt-ampere characteristics of 1 µm length and 100 nm diameter NW. Performed calculation showed that gate threshold voltage and current limit values mostly depend on carriers’ concentration rather than on their mobility with good approximation. Due to the latter fact these characteristics of semiconductor NWs can be determined independently.

In consideration of fixed NW conductivity $\sigma$, figure 4 (a) shows the dependence of drain-source current from potential applied between these contacts in the presence of gate contact. Value of transistor saturation current depends on the combination of carriers’ concentration and their mobility. Lowering carriers’ concentration increases the volume of depletion region, which in turn leads to increasing of NW electrical resistance and decreasing of drain-source current. Figure 4 (b) indicates the dependence of drain-source current from gate voltage under varying values of carrier concentration and mobility. Figure 4 (c) shows the dependence of drain-source current from gate voltage for different values of NW’s mobility in consideration of fixed NW carriers’ concentration. It’s clear that at fixed value of transistor On/Off ratio, the threshold voltage depends on carriers’ concentration rather than on their mobility.

Figure 4 (a, b, c, d). Calculated volt-ampere characteristics of 1 µm length and 100 nm diameter NW. (a) The dependence of drain-source current from drain-source voltage in the presence of gate contact, (b) the dependence of drain-source current from gate voltage at fixed value of conductivity, (c) the dependence of drain-source current from gate voltage at fixed value of carriers’ concentration. (d) The symmetrical model of NW with contacts in MESFET structure.
4. Summary
Arrays of GaN NWs with different doping level on Si substrate were synthesized by means of molecular beam epitaxy. Ohmic contacts connected to single NW transferred to fused silica substrate were made by electron beam lithography, metal thermal evaporation and rapid temperature annealing. Conductivity of undoped and n-doped GaN NWs was estimated to be 0.05 S/cm and 0.5 S/cm, respectively. Based on analysis of collected experimental data and results of numerical modelling, realistic estimation of carrier concentration and mobility of single GaN NWs grown under varied conditions could be made using MESFET measurement circuit layout. Obtained data opens perspectives to solar cells with top junctions in the form of nitride nanowire arrays with controllable composition and doping level.

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