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Uniform hot-wall MOCVD epitaxial growth of 2 inch AlGaN/GaN HEMT structures

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Abstract

The hot-wall metalorganic chemical vapor deposition (MOCVD) concept has been applied to the growth of $Al_xGa_{1-x}N$/GaN high electron mobility transistor (HEMT) device heterostructures on 2 inch 4H-SiC wafers. Due to the small vertical and horizontal temperature gradients inherent to the hot-wall MOCVD concept the variations of all properties of a typical HEMT heterostructure are very small over the wafer: GaN buffer layer thickness of 1.83 μm ± 1%, Al content of the $Al_xGa_{1-x}N$ barrier of 27.7 ± 0.1%, $Al_xGa_{1-x}N$ barrier thickness of 25 nm ± 4%, sheet carrier density of $1.05\times10^{13}\,\mathrm{cm}^{-2}$ ± 4%, pinch-off voltage of −5.3 V ± 3%, and sheet resistance of 449 Ω ± 1%.
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1. Introduction

The continuous development in III-nitrides metalorganic chemical vapor deposition (MOCVD) and related device processing has made GaN-based transistors and light-emitting diodes (LED) available [1]. These developments trigger higher demands on improving the quality and yield of the epitaxial wafers. Further sophistication of the III-nitrides MOCVD technology may benefit by applying not-explored-so-far growth concepts.

Here, we present the growth of III-nitrides by hot-wall MOCVD. We will show that the technique can support the growth of AlGaN/GaN high electron mobility transistor (HEMT) device heterostructures on a large scale with excellent uniformity. The hot-wall MOCVD process is developed in a reactor that can support a maximum wafer size of 1 × 4 inch. The current development is performed in a 1 × 2 inch wafer configuration.

2. The hot-wall MOCVD concept

The MOCVD growth chamber normally exhibits a cold-wall design. Large temperature gradients primarily in the vertical but also in the horizontal directions are inevitable in such a chamber, which influence the uniformity of growth rate, doping and composition.

In the horizontal hot-wall MOCVD setup the process gases are forced through a hollow shaped, RF-induction heated graphite susceptor surrounded by insulation (Fig. 1). Previously developed to promote the growth of thick device quality SiC epitaxial material at deposition temperatures between 1400 and 1650 °C [2], the hot-wall (MO)CVD design concept provides intrinsic advantages for lateral and vertical temperature homogeneity as a prerequisite to achieve homogeneous growth.

Recent experiments have shown one order of magnitude smaller vertical temperature gradient close to the wafer surface for the hot-wall vs. cold-wall SiC CVD single wafer reactors, respectively, with significant influence on the gas composition above the wafer surface [3]. Moreover, a large vertical temperature gradient creates a temperature difference between the two faces of the substrate, which results in

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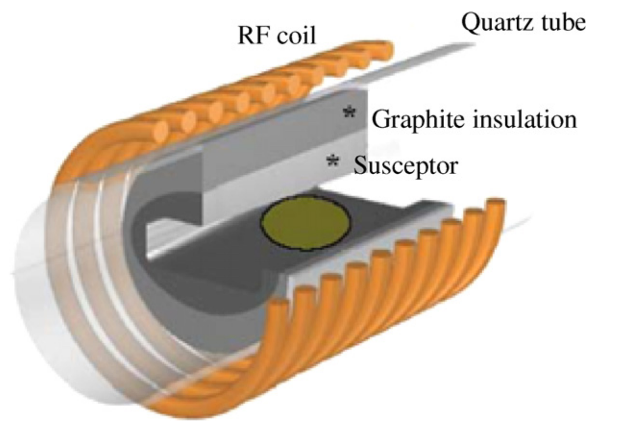

Fig. 1. Schematic view of the hot-wall MOCVD setup, showing the substrate in the hot zone. All precursors (TMAl/TMGa + NH_3) and carrier gases (H_2/N_2) are mixed before the growth chamber.

a bowl-shaped appearance of the substrate during growth [4]. In heteroepitaxy this will add to the strain in the epitaxial layers when the substrate becomes flat again after growth. The concentration gradient of species adjacent to the wafer surface will vary more in the cold-wall case due to larger lateral temperature variations than in the hot-wall case for which homogeneous temperature profile over large deposition area could be achieved [5]. In the horizontal hot-wall MOCVD design, as the temperature gradients and free-convection driven effects [6], are reduced, better spatial uniformity over the deposition area is possible.

3. Epitaxial growth and characterization

The HEMT epitaxial layer structure grown on semi-insulating 4H–SiC substrate starts with a monocrystalline AlN nucleation layer (~100 nm thick) to reduce the misfit between SiC and GaN buffer layer (~2 μm thick). About 25 nm thick $Al_xGa_{1-x}N$ barrier on top of the GaN buffer layer forms the two-dimensional electron gas (2DEG) at the $Al_xGa_{1-x}N$/GaN interface. The structures were grown at a total reactor pressure of 50 mbar in a mixture of H_2 and N_2 carrier gases. The wafer was rotating during growth. Ammonia, NH_3, as a precursor for N, and trimethylaluminum (TMAl) and trimethylgallium (TMGa) as precursors for Al and Ga, respectively, were delivered at V/III ratio in the range of 1045 (AlN growth, NH_3 flow rate of 2 slm) and 385 (GaN growth, NH_3 flow rate of 4 slm). The susceptor temperature was 1100 °C (AlN growth) and 1000 °C (GaN and $Al_xGa_{1-x}N$ growth). The design of the system foresees joint delivery and mixing of the precursors in a cool upstream region.

The thickness of the GaN layer is of the order of micrometers, therefore, it is conveniently measured (and mapped over the whole wafer) using an interference technique. The light from a white LED emitting in the spectral region 410–710 nm is directed via a fiber to the surface of the sample at normal incidence and the light reflected normal to the surface is collected using fiber and send to a monochromator. The reflected light shows clear interference fringes due to the interference of the light beams reflected from the surface and from the interface with the SiC substrate. The incident beam can easily be focused down to less than $\Phi = 0.5$ mm spot; thus the routine thickness mapping is performed on a 1×1 mm grid covering the whole wafer, which gives 1868 measurements points for 2 inch wafers.

The Al content, x, of the $Al_xGa_{1-x}N$ barrier is mapped using low-temperature photoluminescence (PL) at 2 K. The measurement spot is $\Phi \sim 100$ μm. The grid used for mapping is 5×5 mm, which gives 69 measurement points for 2 inch wafers.

The energy position of the $Al_xGa_{1-x}N$ near-bandgap emission depends on the Al content and it is described by the following empirical formula [7]:

$$E_{Al_xGa_{1-x}N} = xE_{AlN} + (1-x)E_{GaN} - bx(1-x).$$

Here, $E_{AlN} = 6.27$ eV and $E_{GaN} = 3.473$ eV are the peak positions of the near-bandgap emission at 2 K of AlN and GaN, respectively, $E_{AlxGa1-xN}$ is the measured peak position of $Al_xGa_{1-x}N$, and b is the so-called bowing parameter. Bowing parameter variations within $b = (0.62 \pm 0.45)$ eV have been previously reviewed and discussed in relation to different growth schemes and material quality [8]. The present measurements are fitted by a bowing parameter of $b = 0.8$ eV.

The GaN layer thickness and Al content of the $Al_xGa_{1-x}N$ determined in the way described above correlate well with reference measurements performed on a batch of samples by secondary ion mass spectrometry (SIMS).

Mercury probe capacitance–voltage (CV) measurements were used to extract information on the 2DEG sheet carrier density, $n_s (n_s = (1/qA) \int C\,dV$, where q, A, C, and V are the elementary charge, contact area, capacitance and bias voltage, respectively), and the pinch-off voltage, V_p, as well as the thickness, t, of the $Al_xGa_{1-x}N$ barrier. In addition, we could determine that the GaN buffer layer was semi-insulating with a net doping concentration less than $1 \times 10^{14}\,cm^{-3}$. The measurements were done at 10 kHz with a 1 mm diameter mercury contact. An ε value of 8.9 was used.

The sheet resistance, R_sq, was measured using a non-contact eddy current technique. The measurement point was 12 mm in diameter.

4. Results and discussion

The thickness of the GaN buffer layers was determined across a full 2 inch wafer *with no edge exclusion zone* and the GaN thickness variation is defined by the expression: (standard deviation)/(mean value) × 100 [%]. The process development from growth runs performed on 2 inch wafers has resulted in thickness variation, which is typically less than 1% (Fig. 2(a)) with best value of 0.4% and is independent of V/III ratio and growth rate, which

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