➢ In-situ/ex-situ X-ray diffraction study of layered III-nitride nanostructures during and after exposure to high temperature. (E, Salamo)

A typical HEMT structure consists of a stack of two semiconductor layers with different energy band gaps. Here we take the example of the for AlGaN/GaN interface. The concentration and the confinement of the two-dimensional electron gas (2DEG) located at the AlGa(In)N/GaN interface are very sensitive to a number of physical properties, such as, the alloy composition and strain. Both have a significant influence on the electron mobility and therefore on the Hall sensor or HEMT performance.

As a result, the structural quality of the AlGaN/GaN layered system and its interfaces are strongly influenced by the interdiffusion effects that impact our Hall sensor. Therefore, the monitoring of the structural modifications occurring at the interface are crucial for the quality control and technical process optimization. By using high-resolution X-ray diffraction as a function of temperature, the influence of heat on our Hall sensor and HEMT performance will be studied. We are concerned with both devices because our plan is to fabricate both the Hall sensor and HEMT during one growth cycle on one substrate. More specifically, by measuring the reciprocal space maps (RSMs) and ω/2θ scans using PIXcel detector while annealing the sample under ambient condition (in-situ) in a wide range of temperatures, or at fixed temperature during long period of time, the following parameters will be monitored in the real-time:

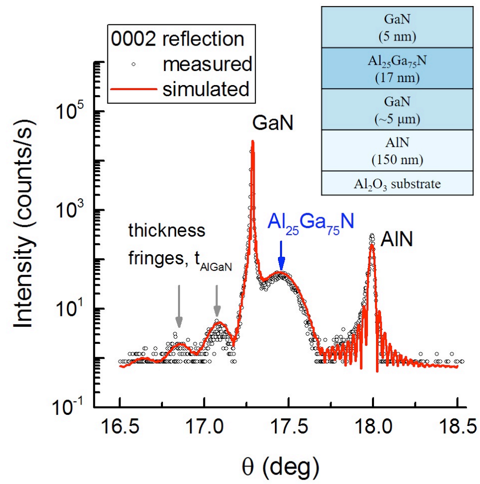

Fig.1. AlGaN/GaN HEMT structure and the 0002 ω/2θ scan shown in red with corresponding data shown with dots. Insert shows AlGaN/GaN structure as Hall sensor.

- Changes in layer composition during solid-solid and solid-gas reactions;
- Activation energy and the diffusion kinetics in the layers vs. annealing temperature; and
- Time evolution of crystal quality (cell parameters, crystallite size, lattice strain).

The composition of the AlGaN barrier can be accurately determined by simulating the measured ω/2θ diffraction profiles [1]. Studying the thermal activated interdiffusion in multilayers make use of the evolution of the ω/2θ diffraction peaks intensity (Fig.1) with temperature or time. The effective interdiffusion coefficient D is calculated via the following equation:

$$D = -\frac{c^2}{8\pi^2}\frac{\mathrm{d}}{\mathrm{dt}}\ln\big(I(t)\big) \quad (1)$$

where c is the lattice parameter of the barrier layer, t is the annealing time and I(t) is the integrated intensity of the barrier layer peak at annealing time t. From the temperature dependence of D, the activation energy E_a is extracted assuming Arrhenius behavior, where D_0, k, and T are the pre-exponential factor, Boltzmann constant, and annealing temperature, respectively.

$$D = D_0 e^{-\frac{E_a}{kT}} \quad (2)$$

Students will pursue a comprehensive x-ray and Hall Effect study to determine the strain and temperature behavior at the crucial two dimensional electron gas interface of AlGaN/GaN sensor and HEMT devices. For example, students will study several samples to determine the strain and temperature of our grown

AlGaN/GaN sensors and HEMT structures and learn the underlying physics by comparing with a physical model that also includes the effect of temperature and strain on important semiconductor parameters like 2DEG carrier mobility. For example, by plotting the logarithm of D as a function of 1/T the activation energy for Al-Ga interdiffusion can be extracted from the slope of the graph. The results obtained from in-situ X-ray diffraction can be compared with electrical properties of processed HEMT structures annealed ex-situ in the same conditions. These results provide information about the layered III-nitride nanostructures and interface stability for further thermal processing, like ohmic contact annealing or dopant activation.

A. V. Kuchuk et al., "Nanoscale Electrostructural Characterization of Compositionally Graded Al x Ga 1– x N Heterostructures on GaN/Sapphire (0001) Substrate," ACS Appl. Mater. Interfaces, vol. 7, no. 41, pp. 23320–23327, Oct. 2015.