

Digital Epitaxy: Femtosecond Pulsed-Laser Deposition for Novel III-Nitride Multilayers

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III-Nitrides present many opportunities for novel devices and materials, limited only by our ability to control the mechanism of deposition and growth. Examples range from multilayers to self-assembled quantum dots. In this presentation, we report a new approach to meet this challenge. We exploit the power of *ultrafast lasers* to provide unprecedented control over the kinetics of the deposition process. This provides the conditions that are critical to the special requirements for III-Nitride growth including ion-energy distributions, electron temperature, precise layer thickness, and interface definition.

A highly-instrumented laser-MBE growth system has been developed for epitaxial deposition of III-Nitride multilayer materials using femtosecond pulsed-laser deposition (Figure 1). The system is turbo-molecular pumped and operates from a base pressure of 5×10^{-9} Torr together with a conventional sample transfer load-lock. A four-element rotating multi-target holder allows different materials to be positioned into the laser beam for ablation-plasma generation and associated deposition of successive layers. The ablation plume is transported through 1 mTorr of activated nitrogen gas which is triggered by the laser plasma burst and sustained with a high-voltage discharge. The growth substrate may be continuously rotated and heated up to 1000°C and also rastered vertically (y) for uniform film growth over 2-inch diameter wafers. Translational positioning micrometers (x & z) allow precise alignment of the film surface for *in-situ* ellipsometry and RHEED measurements. Additional diagnostics for analyzing the deposition plasma include Langmuir probe, optical emission spectroscopy, and ion energy analysis.

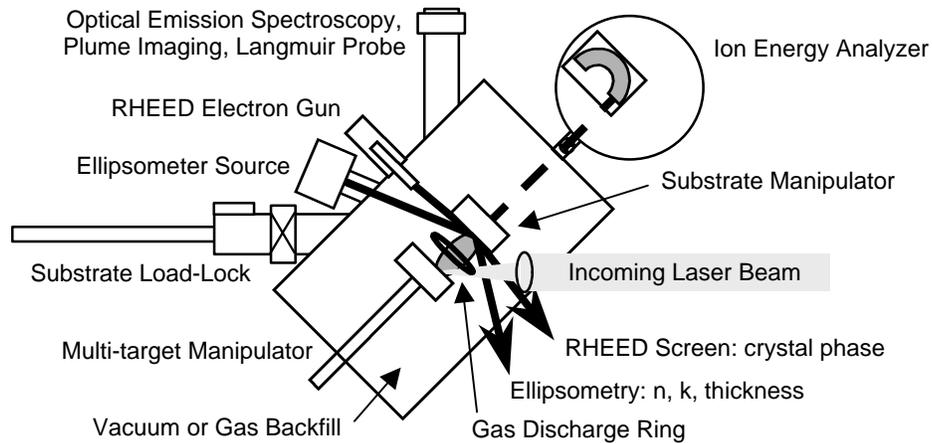


Figure 1. Laser-MBE system for thin-film deposition and ablation-plume analysis.

Figure 2 shows an example of ion energy spectra taken, as a function of charge-state, for the deposition of boron nitride under typical gas-discharge conditions. It is seen in the figure that charge states 1 through 3 are present with a predominance of charge-state 1 for boron and all 3 charge-states for nitrogen. It is also seen in the figure that the ions carry a significant amount of kinetic energy. The relative number and kinetic energy of these ions are a strong function of the energy fluence in the laser pulse and therefore can be adjusted accordingly. In addition to the ions, optical-emission spectra demonstrate the presence of a high percentage of excited neutral atoms in the deposition plume. It is estimated that the neutral species are on the order of a factor of 10 to 20 more abundant than the ions. These neutral species are estimated to have energies in the range of 10's of eV based on time-of-flight plasma refractive index measurements. This is precisely in the range that is needed for the strongly-bonded nitride systems.

Several of the III-Nitride compound semiconductors are presently under investigation with this facility. They include GaN, AlN, and BN. The present experiments are directed at understanding the use of domain epitaxy as a tool for growing these nitrides on dissimilar materials with nominal or marginally-close lattice matching. To this end, multilayers are deposited on crystalline MgO, Al₂O₃, TiN, and Si. Our interest is in fabricating the cubic form of the compound nitride semiconductors through crystal-field-driven structure control. An example of that approach is shown in Fig. 3 where a multilayer array of TiN/BN, grown on <100> silicon, is shown in high-resolution TEM. Through the principles of domain epitaxy, it is observed that a film may be epitaxially-grown on a dissimilar substrate if its unit cell dimension is an integral multiple of the substrate lattice parameter in one or two dimensions. This is observed to occur with lattice mismatches in a range of up to 2.5%. In the case of Fig. 3, the cell dimensions are such that a lattice mismatch of 2.4% exists between Si and TiN with an additional 2.1% between TiN and c-BN. Thus by using the domain-matching technique, one can grow an epitaxial cubic phase of BN that is essentially matched to the silicon substrate with a total lattice parameter mismatch of 4.5% between the two.

In summary, the approach we demonstrate here offers important advantages for III-Nitride thin films. These include: tunable ion-neutral species energetics, digital control of layer thicknesses and the ability to perform *in-situ* time-resolved characterization. This work was supported in part by the National Science Foundation through the Center for Ultrafast Optical Science under grant STC PHY 8920108.

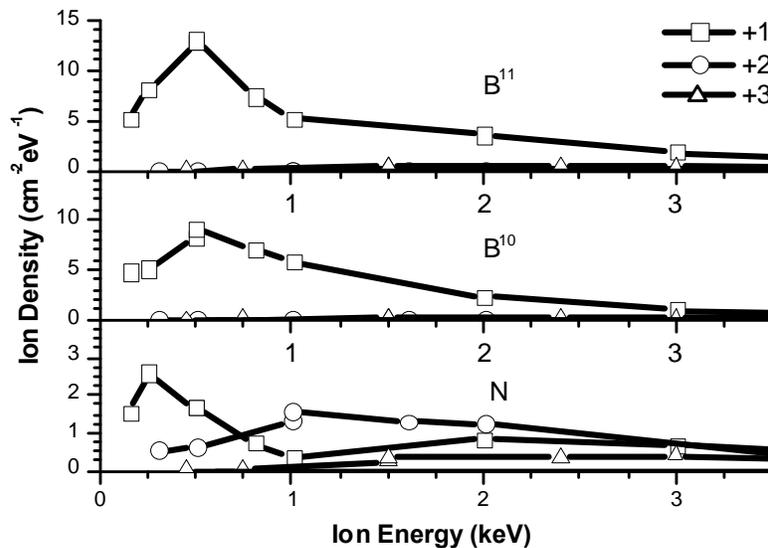


Figure 2. Ion distributions for BN ablation with 200fs, 780nm, 20 J/cm² laser in 0.7mTorr N₂ backfill.

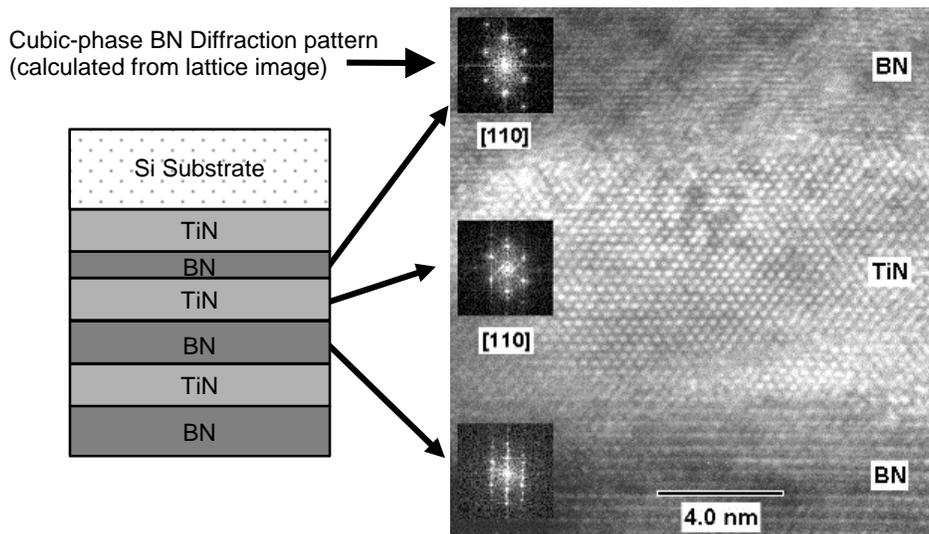


Figure 3. Cross-sectional HRTEM for TiN/BN multilayer film.