Nitrogen Plasma Source for Molecular Beam Epitaxy of Gallium Nitride

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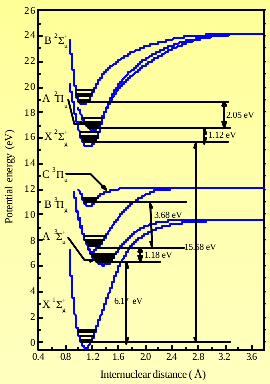
PROJECT MOTIVATION

Investigate the production of reactive nitrogen species in a helicon discharge with the objective using a helicon source for Molecular Beam Epitaxy (MBE) growth of GaN while modifying and controlling the relative fractions of various nitrogen states (molecular, atomic, and ionic) in the plasma.

Required Steps:

- **Determine which plasma species are most favorable for GaN film growth, how their kinetic energy can be controlled, and if they survive long enough to be transported from the plasma source to the growth surface.**
- **Generate specific reactive nitrogen species for film growth by controlling the electron energy distribution function in the plasma through fine tuning of the rf driving frequency and the source magnetic field.**
- **Look for correlation between the dominant specie in the plasma flux reaching the substrate, GaN film quality, and GaN film growth rate.**
- **Explore and understand dependencies of the surface reaction mechanism on nitrogen reactive species, species kinetic energy, and species flux to the substrate as well as on pre-nitridation of the substrate and the substrate temperature.**

EXCITED NITROGEN SPECIES

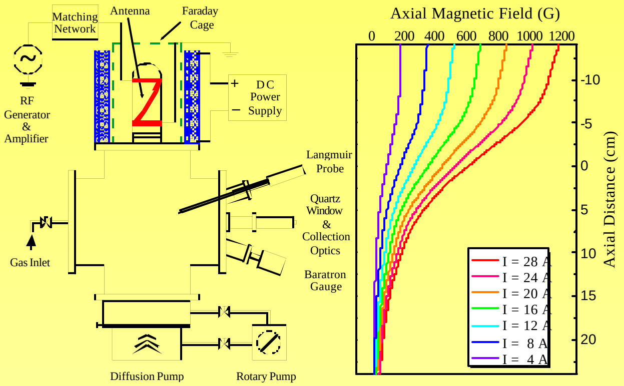


Excited molecular nitrogen states, energies and atomic distances

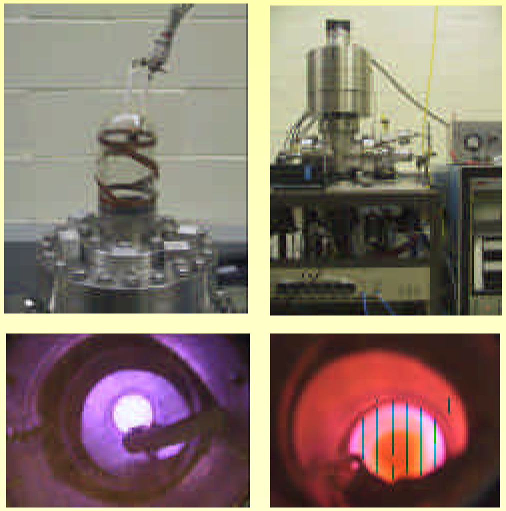
The table below shows competing reactions in low temperature N_2 plasma. Reaction I corresponds to the electron excitation of the N_2 molecule to any neutral excited molecular states. The reaction cross-section corresponds to the total excitation cross-section involving the N_2 molecule (sum of the 10 largest excitation cross-sections for the N_2 molecule). Reaction Ia corresponds to the excitation of the triplet molecular state $A^3S_u^+$, which is the first excited molecular level of the N_2 molecule. Reactions II, III and VI are associated with the break-up of the N_2 molecule into two nitrogen atoms. Reaction II results in the formation of two ground state atoms (^4S), while IIIa and IIIb results in the formation of one metastable nitrogen atoms (^2D at 2.38 eV and ^2P at 3.58 eV above ground state) and one ground state N atom, respectively. Reaction VI involves both the break-up and subsequent ionization of a nitrogen atom. Reaction V describes the ionization of the nitrogen molecule, producing the molecular ion N_2^+. Reaction IV concerns the ionization of atomic nitrogen.

I)	$e^- + N_2 \rightarrow N_2^* + e^-$	($E_{th} \geq$ 6.17 eV)	(Excitation)
Ia)	$e^- + N_2 \rightarrow N_2^*(A^3\Sigma_u^+) + e^-$	($E_{th} \geq$ 6.17 eV)	(Excitation)
II)	$e^- + N_2 \rightarrow N(^4S) + N(^4S) + e^-$	($E_{th} \geq$ 9.76 eV)	(Dissociation)
III)	$e^- + N_2 \rightarrow N^* + N(^4S) + e^-$	($E_{th} \geq$ 12.14 eV)	(Dissociative Excitation)
IIIa)	$e^- + N_2 \rightarrow N^*(^2D) + N(^4S) + e^-$	($E_{th} \geq$ 12.14 eV)	(Dissociative Excitation)
IIIb)	$e^- + N_2 \rightarrow N^*(^2P) + N(^4S) + e^-$	($E_{th} \geq$ 14.34 eV)	(Dissociative Excitation)
IV)	$e^- + N \rightarrow N^+ + 2e^-$	($E_{th} \geq$ 14.55 eV)	(Atomic Ionization)
V)	$e^- + N_2 \rightarrow N_2^+ + 2e^-$	($E_{th} \geq$ 15.58 eV)	(Molecular Ionization)
VI)	$e^- + N_2 \rightarrow N^+ + N(^4S) + e^-$	($E_{th} \geq$ 24.32 eV)	(Dissociative Ionization)

CHEWIE PLASMA SOURCE



Left: A sketch of the experimental apparatus showing the CHEWIE helicon source, the expansion chamber, and the diagnostics access; Right: Axial magnetic field strength versus axial position inside the CHEWIE helicon plasma source and expansion chamber



Top Left: CHEWIE glass tube and antennae; Top Right: the CHEWIE device with diagnostics Bottom: Plasmas in CHEWIE, argon (left) and nitrogen (right). Helicon mode was obtained for argon discharges.

OPTIMAL SOURCE PARAMETERS FOR NITROGEN

For the RF frequencies typically used in helicon sources, the cold plasma dispersion equation has two roots.

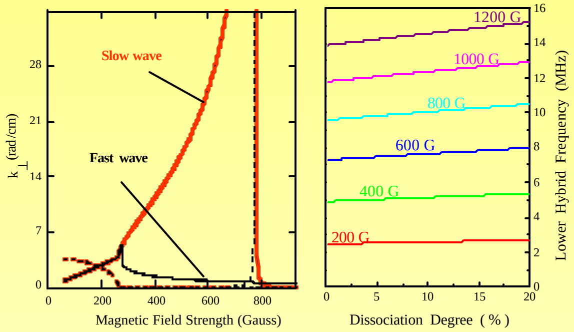
$$r^4 - (a + b)\, r^2 + ab + gd = 0$$

where $a = e_1 - N^2 - e_2^2/e_1$, $b = e_3(1 - N^2/e_1)$, $g = Ne_2e_3/e_1$, $d = Ne_2/e_1$, $N = k_{||}c/w$, and the e's are components of the cold plasma dielectric tensor.

Previous WVU experiments have confirmed that optimal plasma production occurs when the source is operating at or near the lower hybrid frequency

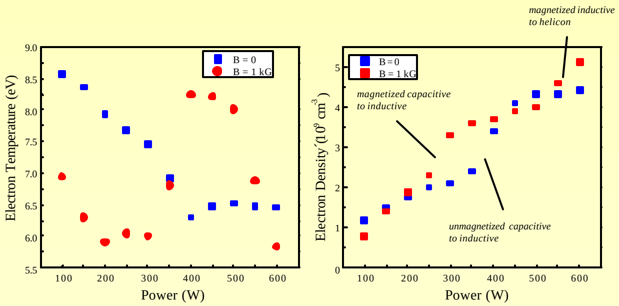
$$w_{LH}^{-2} = (w_{ce}w_{ci})^{-1} + (w_{pi}^2 + w_{ci}^2)^{-1}$$

where w_{ce}, w_{ci} are electron and ion cyclotron frequencies, respectively, and w_{pi} is ion plasma frequency. At the lower hybrid frequency, the slow wave (the Trivelpiece-Gould wave) has a resonance and is strongly damped. For a molecular plasma, the lower hybrid frequency also depends on the degree of dissociation of the gas.



Left: Solutions of the cold plasma dispersion relationship for $k_\wedge$ with $n = 5 ´ 10^{12}$ cm^{-3}, $k_|$ = 0.26 rad cm^{-1}, f = 9 MHz and no collisions. (¾) absolute value of real $k_\wedge$ for the slow wave. (- - -) absolute value of imaginary $k_\wedge$ for the slow wave. (¾) absolute value of real $k_\wedge$ for the fast wave. (- - -) absolute value of imaginary $k_\wedge$ for the fast wave; Right: Lower hybrid frequency of nitrogen plasma for different dissociation degrees and magnetic field strengths in the source.

CHARACTERISTIC MODE TRANSITIONS



Electron temperature (left) and electron density measured in the expansion chamber (right) for 14.2 MHz argon plasma at pressure = 20 mTorr for B = 0 and B = 1 kG.

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