Minority Carrier Lifetime Studies in Heavily Beryllium-Doped p-type GaAs

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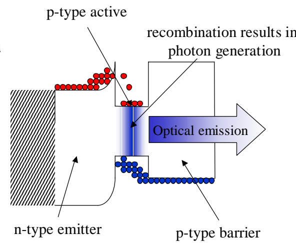
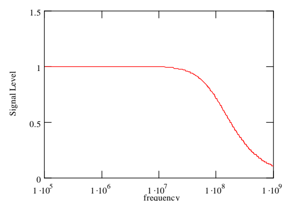
Fundamentals of Light Emitting Diodes (LED) and Limitations on High Speed Performance

GaAs LED's are well suited for application in inexpensive optical data links. The high speed performance of the LED is effected by the minority carrier recombination lifetime within the it's active region (light generation region). This project focuses on the influence of beryllium p-type doping beyond N_A=5x10^{19} on the different mechanisms of carrier recombination.



LED Modulation Bandwidth



$$|I(\omega)| := \frac{I(0)}{\sqrt{1+(\omega\cdot\tau_{rec})^2}} \quad \text{Eq. 1}$$

$$f_{3dB} := \frac{1}{2\cdot\pi\cdot\tau_{rec}} \quad \text{Eq. 2}$$

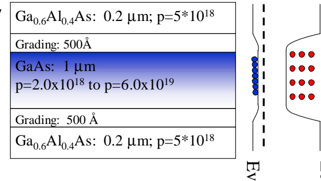
$$\frac{1}{\tau_{rec}} := \frac{1}{\tau_{rad}} + \frac{1}{\tau_{nr}} + \frac{2\cdot s}{w} \quad \text{Eq. 3}$$

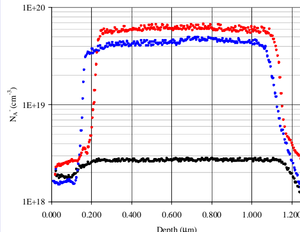
$$\tau_{rad} := \frac{1}{B\cdot N_A} \qquad \tau_{Auger} := \frac{1}{C\cdot N_A^2} \quad \text{Eq. 4}$$

The LED modulation bandwidth is defined as the frequency in which the signal power has decreased by half from its DC value, where the electrical signal power is proportional to the square of the optical intensity (Eq. 1 & 2). It's value is inversely proportional to the minority carrier recombination lifetime of the active region. Note that the minority carrier lifetime of the semiconductor τ_{rec} has both a radiative component τ_{rad} and a non-radiative component τ_{nr}. The final term in equation 3 represents the effects of surfaces on the the total τ_{rec}. Clearly, if any one term in Eq. 3 is significantly less than the others it will dominate the lifetime τ_{rec}. For efficient high-speed LED's that term needs to be τ_{rad}. Equation 4 illustrate how the radiative and Auger recombination (a significant non-radiative mechanism for high doping levels) vary with doping.

GaAs Minority Carrier Lifetime Characteriztion Test Sample Design

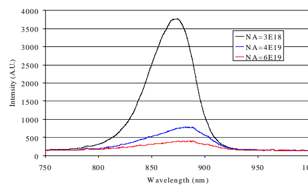
Samples were developed and grown using Molecular Beam Epitaxy (MBE) at Yale to study the recombination properties of heavily doped GaAs. The GaAs region under test was situated between two heterojunctions of AlGaAs so as to confine the photo-generated electrons to the GaAs and to minimize surface recombination effects.





Electrochemical Capacitance Voltage (ECV) profiling is used to verify the doping level in the samples. One sample was grown with N_A=2×10^{18} as a reference sample to compare against other more heavily doped samples. The heavily doped samples were doped $N_A \cong$ 4×10^{19} and $N_A\cong$6×10^{19}. Previous work has predicted that Auger non-radiative recombination begins to dominate around N_A=6×10^{19}.

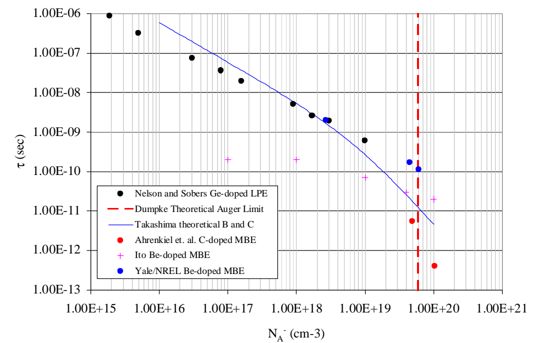
When room temperature excitation photoluminescence (PL) was performed on these sample the PL intensity dropped off significantly with increased doping level. This suggest that a non-radiative recombination mechanism is dominating at high doping levels.



Research done in collaboration with
Robert Koudelka, Sam Chen, and Brian Keyes of the National Renewable Energy Laboratory

Research Supported By Lightspin Technologies and I.B.M.

GaAs Lifetime Versus p-type Doping Concentration



Summary: The lifetime versus doping concentration presented above represents over 40 years of study. The dashed red line is the theoretical doping limit predicted by Dumke for the onset of Auger non-radiative recombination lifetime dominated GaAs. The seminal work on lifetimes measured by Nelson and Sobers in GaAs for doping levels between N_A = 1×10^{15} -1×10^{19} is also presented here along with the expected result from theoretical B and C coefficients. Recent work reported by Ahrenkeil et. al. in carbon doped MBE grown material for the N_A = 1×10^{19} -1×10^{20} regime is presented. It was reported that these short lifetimes were probably caused by Auger recombination. The samples grown at Yale were measured by the same group at the National Renewable Energy Laboratory that measured Ahrenkiel's. Note that the lifetime in the beryllium doped material is significantly longer that the carbon doped material. These lifetimes also appear to be too long for Auger recombination when compared with the theoretical C coefficient. We also believe that these are the longest lifetimes ever reported for p-type GaAs doped around N_A = 5x10^{19}. Although no complete explanation exist for the contradiction between the measured lifetimes and the PL intensity, we are enthusiastic about this result. Auger recombination would be difficult if not impossible to preclude once it begins to dominate in an LED. However, if the non-radiative component that exist in these samples is not Auger as the data suggest and is due to another impurity or defect in the crystal there still exist an opportunity to remove this non-radiative effect by changing MBE growth parameters and doping with Beryllium. This could have the result of extending the the bandwidth capabilities of high brightness LEDs for data transmission applications.