THZ EMISSION SPECTROSCOPY OF NARROW BANDGAP SEMICONDUCTORS

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ABSTRACT

This dissertation presents a model for emission of electromagnetic transients in the terahertz (THz) region from optically excited narrow bandgap semiconductors. This model explains the THz emission from the surface field acceleration mechanism and from the photo-Dember effect independently. It relates intrinsic parameters of the semiconductor, namely the majority and minority carrier concentrations and the mobilities, to the radiated THz field. The conditions that enhance the THz emission process in the case of surface field acceleration and in the case of the photo-Dember effect have been clearly identified.

In this work three types of narrow bandgap semiconductors were investigated as sources of THz radiation. First the THz emission from a set of Te doped GaSb samples was studied. GaSb:Te is an interesting material because samples can be grown with a broad range of carrier concentrations. A Ga$_x$In$_{1-x}$Sb ingot was also studied. In this material system the electron mobility and the bandgap range from the GaSb values ($E_g = 0.73\text{eV}$) to the InSb values ($E_g = 0.17\text{eV}$). This is important in order to understand the extent to which the reduced bandgap of InSb is favorable for the THz emission process. This ingot was also used as a demonstration of how the THz time-domain spectroscopy technique can reveal the native defect density distributions in this ingot. Additionally the THz emission from InN was studied. The recently revised bandgap value of InN make it a good material for optically excited THz emission. In order to investigate the ultrafast scattering mechanisms in InN, an ultrafast photo-reflection setup was used. Subpicosecond non-radiative recombination was observed in silicon doped InN films.
1. Introduction

Terahertz Time-Domain Spectroscopy (THz-TDS) has emerged as an important and powerful spectroscopic technique over the last decade[3]. It uses ultrafast laser pulses to generate electromagnetic transients of frequencies in the THz region and performs a time-resolved detection of them. A typical THz-TDS setup is an optical pump-probe[4] arrangement.

Applications of THz-TDS have been demonstrated in areas such as medical imaging [5], non-destructive testing[6] and high sensitivity gas spectroscopy[7]. One of the most significant advantages of THz-TDS over other imaging techniques is that the photon energy in this frequency range is low. This is attractive for medical and biological applications in contrast to the ionizing effects of X-rays widely used for medical imaging. Another fundamental advantage of the THz region is the fact that many physical processes, such as rotational excitations in gases[7] and vibrations in many inorganic[8] and organic[9] crystalline structures, take place in this spectral region. However, all these applications are currently limited by the power of available sources[10] of THz radiation. The development of brighter, high bandwidth THz radiation sources is important in order to expand the applications of these techniques.

There are two types of THz emitters based on optical excitation by femtosecond laser pulses. The first type uses semiconductors where a femtosecond laser pulse is absorbed and the generated photocarriers are accelerated by an intrinsic or extrinsic electric field radiating electromagnetic transients in the THz region. The second type of THz emitter uses a crystal where the femtosecond laser pulse suffers a non-linear process known as optical rectification, which leads to THz pulse emission.

The topic of this dissertation is the optically excited THz emission from narrow bandgap semiconductors and the dependence of this process on the semiconductor properties. The complete understanding of the THz emission process is important in order to design brighter sources of THz radiation that would broaden the possible applications of this technique and to understand the fundamental limitations in this process. The narrow bandgap semiconductors are technologically important because they are compatible with solid state fiber lasers operating at a wavelength of 1.5µm. This is of interest in order to design compact and portable THz-TDS systems.

Several groups have studied the THz emission process in dependance of extrinsic
factors such as external electric field\cite{11}, magnetic field\cite{12} and temperature\cite{13}. The question that this dissertation addresses is how the strength of THz radiation from a semiconductor surface depends on the intrinsic properties of the material such as the bandgap, carrier concentration, majority carrier type and mobility.

In this work three types of narrow bandgap semiconductors have been investigated. First the THz emission from a set of Te doped GaSb samples was studied. GaSb is a narrow bandgap material that can be grown with high purity. Selective doping techniques in GaSb make this material a good model system to analyze the influence of majority and minority carrier concentrations in the THz emission process. A Ga$_x$In$_{1-x}$Sb ingot was studied in order to understand the extent to which the reduced bandgap of InSb is favorable for the THz emission process. This ingot was also used as a demonstration of the THz-TDS technique to reveal the native defect density distributions.

Additionally, the THz emission from InN has been studied. This material is interesting because the process to grow high quality InN films is new\cite{14}. This development lead to the revision of the fundamental bandgap of InN from $\sim2.0\text{eV}$ to the current value of $0.68-0.8 \text{eV}$. For this reason, InN is now regarded as a narrow bandgap material. Further, InN is an interesting semiconductor material because the band structure has very high satellite valleys compared to the fundamental bandgap, therefore there is a very low probability of intervalley scattering. These two properties make InN a good material for optically excited THz emission. Among the factors that affect the efficiency of the THz emission process are the ultrafast scattering mechanisms. In order to investigate these mechanisms in InN, an ultrafast photo-reflection setup was used. Changes in the reflectivity can reveal carrier scattering phenomena in the ultrafast regime.

Following this introduction, an outline of the two main theoretical models of THz emission from semiconductor surfaces will be given. These are the surface field acceleration model and the photo-Dember effect. Later, the transient photo-reflection principle is described and then an outline of the relevant scattering mechanisms that account for the ultrafast carrier mobility is presented.

Next is a description of the experimental arrangements employed. The details of a THz-TDS and ultrafast photo-reflection setups are explained therein. Additionally, the semiconductor sample growth and preparation are described. This is followed by the experimental results. The emission from Te doped GaSb is analyzed and it is demonstrated that both emission mechanisms, surface field acceleration and photo-Dember effect, are
present in this material system. Further, the efficiency of each of these mechanisms depends on the carrier concentration in the bulk. Then the InN results are presented. They are interesting because they reveal that InN is a promising THz surface field emitter due to a strong surface accumulation layer[15] and due to the absence of intervalley scattering. Ultrafast photo-reflection measurements on InN suggest the presence of non-radiative recombination centers.
2. Terahertz Time-Domain Spectroscopy

In this work the THz region will be referred to as the spectral region ranging from 100 GHz to about 10 THz as shown in figure 2.1. The wavelengths in this region range from 3mm to 30µm. This classification is not unique and is based on the typical bandwidth of a THz-TDS setup.

There are several distinctive advantages of the THz-TDS system when compared to other continuous wave techniques in the far infrared region such as Fourier Transform Infrared Spectroscopy (FTIR)[16]. In the FTIR technique a sample is placed in an interferometer where one of the interferometer arms is scanned. Generally a helium cooled bolometer is used for detection. The THz-TDS setup is based on an optical pump-probe arrangement where the probe laser beam and the THz beam coincide in space and time at the THz detector. This coherence of the pump-probe setup can achieve very high signal to noise ratios. Another distinctive advantage of the time-domain setup is the ability to resolve the electric field phase. Electric field polarity can be distinguished in THz-TDS systems.

Signal to noise ratios from $1 \times 10^3$ to $1 \times 10^4$ are common in THz-TDS systems. In order to compare this value to other light intensity detectors it must be kept in mind that THz-TDS is a field detector, therefore a signal to noise ratio of $1 \times 10^4$ in electric field is equivalent to a light intensity dynamic range of 80dB. Despite the high sensitivity of the THz-TDS technique, applications are still limited by the power of available THz emitters. In order to materialize the full potential of this technique it is necessary to find brighter sources of this radiation.

Several semiconductor materials have been investigated as THz sources under optical excitation. Early experiments by Auston et al.(1984)[17] used radiation damaged silicon

![Figure 2.1: Electromagnetic spectrum sketch showing the range of frequencies accessible by the THz-TDS technique.](image)
to create optically excited picosecond transients. These experiments used a biased dipole structure to emit and detect the pulses. THz emission from unbiased semiconductor surfaces was reported by Zhang et al. (1990) and by several other groups after. InAs, InP, GaAs, GaSb, InSb, CdTe, CdSe, and Ge were used as sources of THz radiation. The built-in field at the surface of these materials was regarded as responsible for the acceleration of the photocarriers resulting in radiation.

Optical rectification and electro-optic sampling were developed as alternative methods to generate and detect THz radiation in this period (1992). In 1995, Dekorsy et al. reported THz radiation from a Te crystal, and the buildup of a photo-Dember field was proposed.

As a general rule it can be stated that all III-V semiconductors of narrow bandgap can emit optically excited THz radiation. It is noteworthy that low-temperature-grown GaAs (LT-GaAs) is currently the most common material for biased THz emitters and detectors. Devices based on LT-GaAs have reached commercial applications in THz-TDS. On the other hand, InAs has been reported as the most efficient unbiased THz surface emitter, and it is widely used in research THz-TDS systems. Next, a model of THz emission from unbiased semiconductor surfaces is presented.

### 2.1 Optically Excited THz Emission Processes

From the two types of optically excited THz emitters, this dissertation focuses on one of them, namely the acceleration of optically injected carriers by intrinsic electric fields in a semiconductor. In this case THz transients from semiconductor surfaces have been associated with two radiation mechanisms: the surface field acceleration and the photo-Dember effect. The surface field arises from surface defects that induce a space charge distribution at the surface of a semiconductor. This space charge distribution generates an electric field that will accelerate the photoinjected carriers resulting in radiation. In the surface field acceleration picture, the THz emission will depend on the surface defect density, the bulk carrier concentration and the mobility of the carriers. A sketch is shown in figure 2.2.a.

On the other hand, the photo-Dember effect is understood as the result of a non-equilibrium carrier distribution. After photo-excitation, carriers have high velocities because the photon energy is larger than the semiconductor bandgap energy. Since electrons and holes have different mobilities, electrons diffuse into the bulk much faster than the
holes, and a space charge distribution is created. From this space-charge region an electric field arises resulting in radiation. In the photo-Dember picture, the THz emission depends on the mobility of electrons and holes, and on the bulk carrier concentration. A sketch is shown in figure 2.2.b. In principle, the photo-Dember effect should not have a significant dependence on the density of surface states.

These two mechanisms have been observed separately in several experimental studies [13, 23, 25, 26, 28]. Experimental evidence such as the polarity reversal of the THz pulse emitted by semiconductor samples of different majority carrier type [23, 25] has been associated with the surface field acceleration as the dominant mechanism. A lack of polarity reversal [23, 25] and a strong temperature dependence of the emission process [13] support the photo-Dember effect as the dominant mechanism. In this thesis, the dependence of each of these mechanisms on the majority and minority carrier concentrations is studied.

Both mechanisms of THz emission are modeled by considering the electromagnetic radiation arising from a transient current density. Figure 2.3 illustrates the assumptions. The laser pulse creates a photocurrent that propagates into the bulk of the semiconductor in the direction normal to the surface (fig. 2.3, $\vec{J}$). The laser pulse has an absorption depth of about 200nm, the laser spot size is about a millimeter and the radiated wavelength is $300\mu m$. The detector is located about a meter away from the emitter. Because the observer is far away in the length scale of the emission process, some simplifications can be applied. It is assumed that the current density is uniform in the x and y axis, therefore it is a function of z only. Then the vector potential from a current density is described as:
\[ \vec{A}(r) = \frac{\mu}{4\pi} \int \frac{\vec{J}}{r} dV \]  

(2.1)

\[ dV = Sdz \]  

(2.2)

\[ \vec{A}(r, t) = A_z = \frac{\mu}{4\pi} \frac{S}{r} \int J(z, t) dz \]  

(2.3)

where \( J \) is the current density and is considered constant over the laser spot size \( S \). The distance from the laser spot to the observer is \( r \), and \( \mu \) is the magnetic permeability of vacuum. Because \( J \) depends on \( z \) exclusively, the only contributing component of \( H \) is the azimuthal.

\[ \mu \vec{H} = \nabla \times \vec{A} \]  

(2.4)

\[ H_\phi = \frac{1}{\mu r} \left[ \frac{\partial}{\partial r} (rA_{\theta}) - \frac{\partial A_r}{\partial \theta} \right] \]  

(2.5)

\[ H_\phi = \frac{S \sin \theta}{4\pi} \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( \int_0^{Bulk} J(z, t) dz \right) + \frac{1}{r^2} \int_0^{Bulk} J(z, t) dz \right] \]  

(2.6)

**Figure 2.3:** The photo-current density on the semiconductor surface and the corresponding radiated fields.
In order to evaluate the derivative, the field must be regarded as a retarded field. The time evolution of the photo-carrier current density depends on many factors such as recombination and scattering events. In order to simplify the problem in a first approximation, the photo-carrier current density is assumed to follow the laser pulse time evolution. The problem is further simplified assuming that the photo-carrier current density follows a Gaussian time evolution. Then the current density can be written as:

\[ J(z, t) = J(z)e^{-\frac{t-r/c}{\tau}^2} \]  

(2.7)

where \( \tau \) is the laser pulse duration. To simplify the calculations, two dimensionless time evolution functions are defined:

\[ \frac{\partial J(z, t)}{\partial r} = J(z)e^{-\frac{t-r/c}{\tau}^2} 2 \left( \frac{t}{\tau} - \frac{r}{\tau c} \right) \frac{1}{c \tau} \]  

(2.8)

\[ e^{-\frac{t-r/c}{\tau}^2} 2 \left( \frac{t}{\tau} - \frac{r}{\tau c} \right) \equiv T_1 \]  

(2.9)

\[ e^{-\frac{t-r/c}{\tau}^2} \equiv T_0 \]  

(2.10)

\[ \frac{\partial}{\partial r} T_0 = \frac{1}{c \tau} T_1 \]  

(2.11)

\[ H_\phi = \frac{S \sin \theta}{4 \pi} \left[ \frac{1}{rc \tau} \int_0^{Bulk} J(z)dz T_1 + \frac{1}{r^2} \int_0^{Bulk} J(z)dz T_0 \right] \]  

(2.12)

The first term in equation 2.12 is radiative, as it depends on \( 1/r \), and the second term is inductive, as it depends on \( 1/r^2 \). Since this model describes radiation where the distance from the radiating current to the observer is much larger than a wavelength, the second term is neglected because it contributes in the near field only.

\[ H_\phi = \frac{S \sin \theta}{4 \pi c \tau} \int_0^{Bulk} J(z)dz \left( \frac{1}{r} \right) T_1 \]  

(2.13)

The electric field can then be calculated as:
\[ \frac{\partial}{\partial t} \epsilon \vec{E} = \nabla \times \vec{H} \] (2.14)

\[ \left( \nabla \times \vec{H} \right)_r \propto \frac{1}{r^2} \] (2.15)

\[ \left( \nabla \times \vec{H} \right)_\phi = 0 \] (2.16)

\[ \left( \nabla \times \vec{H} \right)_\theta = \left[ -\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{S \sin \theta}{4 \pi c \tau} \int J dz \frac{1}{r} T_1 \right) \right] \] (2.17)

\[ \left( \nabla \times \vec{H} \right)_\theta = S \sin \theta \frac{1}{4 \pi c \tau} \int J dz \left( -\frac{1}{r} \right) \frac{\partial}{\partial r} T_1 \] (2.18)

\[ \vec{E} = E_\theta = \frac{S \sin \theta}{4 \pi \epsilon c \tau} \int_0^{Bulk} J(z) dz \left( \frac{1}{r} \right) T_1 = E_{far} \] (2.19)

This result shows how the radiated THz field depends on the photocurrent density.

### 2.1.1 Surface Field Acceleration

After obtaining the far field radiated from a current density, the photocurrent in the case of surface field acceleration is obtained. The THz emission from semiconductors due to surface field acceleration[26] can be modeled under the assumption that the concentration of carriers is constant in the material and that the surface states create a uniform depletion region in the semiconductor. Under these assumptions an homogeneous electric field across the depletion region has the following form:

\[ E_S = \frac{e n}{\epsilon S} (W - z) \quad : 0 < z < W \] (2.20)

\[ = 0 \quad : W < z \]

where \( n \) is the electron concentration. In the case of compensated semiconductors, the expression \( n = |N_D - N_A| \) has been used to account for the majority carrier concentration, since the majority carrier concentration in most cases is several orders of magnitude higher than the intrinsic carrier concentration. The depletion width \( W \) due to band bending is calculated from the surface potential \( V_s[31] \).
\[ W = \sqrt{\frac{2 \epsilon_s (V_s - k_BT/e)}{e |n|}} \quad (2.21) \]

The photocarrier absorption near the surface has been assumed to follow the form \( \Delta n = \Delta \tilde{n} e^{-\alpha z} \). With this expression the drift equation can be written as:

\[ J_{n,p} = e\mu_{n,p} \left( \Delta \tilde{n} e^{-\alpha z} \right) E_s(z) \quad (2.22) \]

The far field radiation from a transient photocurrent density has been derived in equation 2.19. With this expression and equation 2.20 one can obtain the relationship between THz emission due to surface field acceleration and the material parameters:

\[ E_{far} = \frac{Se\mu_{n,p} \Delta \tilde{n}}{4\pi \epsilon_0 c^2 \tau_r} \int_0^{Bulk} e^{-\alpha z} E_s(z) dz \quad (2.23) \]

\[ E_{far} = \frac{Se^2 \mu_{n,p} \Delta \tilde{n}}{4\pi \epsilon_0^2 c^2 \tau_r} |N_D - N_A| \times \left[ W \int_0^W e^{-\alpha z} dz - \int_0^W ze^{-\alpha z} dz \right] \quad (2.24) \]

\[ E_{far} = \frac{Se^2 \mu_{n,p} \Delta \tilde{n}}{4\pi \epsilon_0^2 c^2 \tau_r \alpha^2} |N_D - N_A| \left[ e^{-\alpha W} + W \alpha - 1 \right] \quad (2.25) \]

Here it is shown that the THz emission resulting from surface field acceleration must be directly proportional to the mobility and proportional to the excitation fluence. It also depends on the depletion width and the optical absorption length. Later in the discussion it will be shown that an efficient THz emitter is a semiconductor such that the depletion width equals or extends beyond the optical absorption length.

### 2.1.2 Photo-Dember Effect

The photo-Dember effect describes drift and diffusion currents of electrons \( j_n \) and holes \( j_p \) in an illuminated semiconductor. In this model \([32, 33]\), an electric field arises such that the drift current compensates the faster diffusion of electrons with respect to the holes. If the energy of the exciting photon is well above the bandgap, the remaining energy after absorption will raise the carrier temperature enhancing this effect. The model begins with the diffusion and drift currents:
\[ J_{n,p} = e\mu_{n,p}nE \pm \mu_{n,p}k_BT \frac{\partial n}{\partial z} \]  

(2.26)

The carrier density can be expressed as the bulk carrier density plus the photocarrier density as \( n = n_b + \Delta n \). Then the photo-Dember hypothesis is expressed as:

\[ J_{\text{total}} = J_{\Delta p} + J_{\Delta n} = 0 \]  

(2.27)

From this condition the photo-Dember field \( E_D \) is obtained:

\[ E_D = \frac{k_BT_e}{e} \frac{b\frac{\partial \Delta n}{\partial z}}{p_b + n_b b + \Delta n(1+b)} \]  

(2.28)

where \( b = \frac{\mu_n}{\mu_p} \) is the ratio of mobilities of electrons and holes, \( T_e \) is the carrier temperature obtained from the residual photon energy, and \( p_b \) and \( n_b \) are the bulk electron and hole concentrations. The photo-Dember field is derived under the assumption that the excess energy from the laser photons is transferred to the electrons, therefore the hole temperature is neglected. It is also assumed that the density of photoinjected electrons \( \Delta n \) is equal to the density of photoexcited holes \( \Delta p \) and that \( \frac{\partial p_b}{\partial z} \) and \( \frac{\partial n_b}{\partial z} \) are negligible, that is, the bulk carrier concentration is constant.

\[ E_{\text{Dem}} = \frac{k_BT_e b}{e} \frac{\Delta \tilde{n} \alpha e^{-\alpha z}}{p_b + b n_b + \Delta \tilde{n} e^{-\alpha z}(1+b)} \]  

(2.29)

\[ E_{\text{far}} = \frac{S}{4\pi\varepsilon_0 c^2\tau} \frac{k_BT_e \mu_n}{(1+b)} \left[ \frac{b(n_b - p_b)}{1+b} \ln \left( 1 + \frac{\Delta \tilde{n}(1+b)}{p_b + b n_b} \right) - \Delta \tilde{n} \right] \]  

(2.30)

In conclusion, the photo-Dember emission depends on the carrier temperature after excitation. It also depends on the bulk carrier concentration and on the ratio of electron and hole mobilities. It has been assumed that the photon excess energy is transferred mostly to the electrons due to their smaller effective mass, and as long as this holds true the radiation depends on the electron mobility as an additional factor.
These equations will be used to evaluate the experimental data in the coming sections. Further, it will be shown how each emission mechanism dominates according to experimental and sample conditions such as the majority and minority carrier concentrations.
3. Ultrafast Spectroscopy

3.1 Transient Photo-Reflection

Scattering and recombination mechanisms affect the dynamics of optically generated carriers in a semiconductor material. Unlike direct current approaches to measure scattering such as DC Hall mobility experiments, the high time resolution of a femtosecond optical pump-probe arrangement can be used to investigate ultrafast carrier dynamics in semiconductors[34]. The transient photo-reflection technique is based on the modulated injection of carriers in a semiconductor sample. The observation of the probe beam reflection yields information about the index of refraction of the material. The reflectivity change $\Delta R$ depends linearly on the index of refraction change[35] $\Delta n$:

$$R = \left( \frac{n - 1}{n + 1} \right)^2$$

(3.1)

$$\frac{\Delta R}{R} = \frac{4 \Delta n}{(n^2 - 1)}$$

(3.2)

where $n$ is the index of refraction. The change in the index of refraction may depend on several factors[36] such as band filling effects, bandgap renormalization and free carrier absorption. In this work the quantitative analysis is limited to the free carrier absorption. The index of refraction change can be modeled through an increase in the plasma frequency[35]. This approach gives:

$$\frac{\Delta n}{n} = \left( \frac{2\pi e^2}{\epsilon m^* \omega^2} \right) \Delta n$$

(3.3)

where $\Delta n$ is the density of photoinjected carriers.

$$\frac{\Delta R}{R} = \frac{4n}{(n^2 - 1)} \left( \frac{2\pi e^2}{\epsilon m^* \omega^2} \right) \Delta n$$

(3.4)

Here it can be concluded that the transient photo-reflection signal due to free carrier absorption depends linearly on the photocarrier density. Due to this property and because
of the high time resolution of the ultrafast pump-probe setup, this technique can be used to perform a direct measurement of the carrier recombination rates in the ultrafast regime.

Several recombination processes can take place in a direct bandgap semiconductor. Non-radiative recombination, interband radiative recombination and Auger recombination are possible. Non-radiative recombination\(^{[37]}\) is related to localized recombination centers such as impurities, physical defects and surface defects. The non-radiative recombination lifetime can be expressed through the Shockley-Read-Hall theory\(^{[34]}\) as:

\[
\tau_{nr} = \frac{1}{N_{\text{def}} \sigma_{\text{def}} v_{\text{th}}}
\]  

(3.5)

where \(N_{\text{def}}\) is the density of defects, \(\sigma_{\text{def}}\) is their cross section and \(v_{\text{th}}\) is the carrier thermal velocity. From this equation it can be concluded that for a constant carrier temperature the non-radiative recombination lifetime depends on material and sample parameters (defect density and cross section) and is independent of the photocarrier density.

Interband radiative recombination is proportional to the carrier concentration, and in the case of doped semiconductors the recombination is limited by the minority carrier concentration. The recombination lifetime\(^{[37]}\) is defined as:

\[
\tau_{\text{rad}} = \frac{1}{B n}
\]

(3.6)

where \(n\) is the minority carrier concentration and \(B\) is a proportionality constant. Finally the Auger recombination is the transfer of the electron-hole pair energy to a third carrier. For this reason the Auger recombination time has a higher order dependence on the carrier concentration\(^{[38]}\). In summary, the recombination rates are expressed as:

\[
\frac{1}{\tau} = \frac{1}{\tau_{nr}} + \frac{n_b + \Delta n}{B_{\text{rad}}} + \frac{(n_b + \Delta n)^2}{C_{\text{Auger}}}
\]

(3.7)

This equation is important because in transient photo-reflection experiments the photoinjected carrier density is high compared to the native carrier density. By observing the lifetime dependence on the photoinjection density, it is possible to distinguish among these recombination mechanisms.
4. Scattering Processes in the Ultrafast Regime

In this chapter several processes that affect THz emission from optically excited semiconductor surfaces will be presented. Many direct bandgap semiconductors exhibit THz emission when they are optically excited by femtosecond pulses, however their performance as THz emitters varies dramatically\[26\]. In chapter 2 it was shown that the radiated field strength depends on the electron and hole mobilities. In the quasi-classical approach to electron transport in semiconductors, the mobility parameter is used to describe the scattering events taking place in the material. In general, carriers in a semiconductor suffer the following scattering and recombination mechanisms\[8\]:

- Acoustic phonon
- Optical phonon
- Defect related recombination
- Radiative recombination
- Intervalley scattering

Typically in III-V semiconductors, acoustic phonons have relaxation times in the order of tens of picoseconds\[37\]. In the ultrafast regime (picosecond range), where the THz emission process takes place, it is unlikely that these events occur, therefore this scattering mechanism is immaterial for the THz emission process. Nevertheless, these events will decrease the mobility measured by DC currents through the Hall effect.

Optical phonon emission occurs at shorter times and this form of scattering does influence the THz emission process\[13\]. Further, optical phonons are expected to play a significant role in scattering in III-V semiconductors due to their polar nature. Table 4.1 shows electron-phonon scattering times for some III-V semiconductors.

Non-radiative recombination is a process associated with localized defects. The recombination lifetime for this process is inversely proportional to the defect density as shown in equation 3.5. In semiconductors with a high defect density, such as the InN films studied in this work, the defect-related recombination lifetime can have picosecond and sub-picosecond values, and for this reason it negatively influences the THz emission process.
Table 4.1: Electron-phonon scattering times for some III-V semiconductors

<table>
<thead>
<tr>
<th>Material</th>
<th>Electron-phonon scattering time</th>
<th>LO-phonon scattering time</th>
</tr>
</thead>
<tbody>
<tr>
<td>InN</td>
<td>200fs $^1$</td>
<td></td>
</tr>
<tr>
<td>InP</td>
<td></td>
<td>2.3 ps $^2$</td>
</tr>
<tr>
<td>InAs</td>
<td>450fs $^3$</td>
<td>1.8 ps $^2$</td>
</tr>
<tr>
<td>GaAs</td>
<td></td>
<td>2.5 ps $^4$</td>
</tr>
</tbody>
</table>

Table 4.2: Radiative recombination lifetime for some III-V semiconductors (intrinsic)

<table>
<thead>
<tr>
<th>Material</th>
<th>Rad. Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>InAs</td>
<td>15µs $^5$</td>
</tr>
<tr>
<td>GaSb</td>
<td>9 ms $^5$</td>
</tr>
<tr>
<td>InSb</td>
<td>0.62µs $^5$</td>
</tr>
<tr>
<td>InN</td>
<td>350µs $^6$</td>
</tr>
</tbody>
</table>

Radiative or direct recombination depends on the majority and minority carrier concentrations, but in general the lifetimes for direct recombination in a doped semiconductor are in the nanosecond range and higher. Table 4.2 shows typical recombination lifetimes for some III-V semiconductors. The table shows radiative recombination lifetimes for intrinsic semiconductors. As the density of carriers increases, the lifetime decreases. However the recombination lifetimes do not reach the ultrafast regime, therefore the probability of a radiative recombination event during the THz emission process discussed in this work is very low.

Intervalley scattering is the process by which excited electrons in the conduction band are transferred to the satellite valleys. The effective mass in those valleys is higher than in the Gamma valley, therefore the total carrier mobility is lower when this process takes place. This process is triggered when carriers have an energy comparable to that of the satellite valley minimum.

$^1$From I-V power balance considerations. Ref. [39]
$^2$From Time-resolved Raman Spectroscopy. Ref. [40]
$^3$From phonon-limited mobility. Ref. [41]
$^4$From Time-resolved Second Harmonic Generation. Ref. [42]
$^5$Ref. [43]
$^6$Assuming an intrinsic carrier concentration for InN, 300K, $E_g = 0.77$, Ref.[44]
Table 4.3: Satellite valley energy difference for some III-V semiconductors

<table>
<thead>
<tr>
<th>Material</th>
<th>$\Gamma$ Valley(eV)</th>
<th>L valley(eV)</th>
<th>A valley(eV)</th>
<th>Difference(eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>InN</td>
<td>0.68</td>
<td>3.0 - 4.5</td>
<td>2.6 - 4.7</td>
<td>1.92-4.02</td>
</tr>
<tr>
<td>InAs</td>
<td>0.35</td>
<td>1.08</td>
<td></td>
<td>0.73</td>
</tr>
<tr>
<td>InSb</td>
<td>0.17</td>
<td>0.68</td>
<td></td>
<td>0.51</td>
</tr>
<tr>
<td>GaSb</td>
<td>0.73</td>
<td>0.81</td>
<td></td>
<td>0.084</td>
</tr>
</tbody>
</table>

Figure 4.1: Simplified band structure for GaSb[1], InAs[1] and InN[2]. Intervalley scattering is more likely in GaSb than in InAs, for excitation of 1.5eV photons.

Intervalley scattering has relaxation times in the sub-picosecond scale, and it is especially important in hot carrier diffusion, which is part of the THz emission process from narrow bandgap materials. The relative energies of the L and X valleys with respect to the $\Gamma$ valley for some III-V semiconductors are shown in table 4.3 and in figure 4.1. The displacement of electrons into the side-valleys is adverse for THz emission, because the heavier effective mass of the electron in those valleys decreases the total mobility. Figure 4.1 shows that GaSb has very low side-valley energies, as opposed to the InAs side-valleys. This difference explains the higher efficiency of InAs as a THz emitter with respect to GaSb, when excited with 1.5eV photons. The electrons after excitation with this energy are hot and the probability of intervalley scattering in GaSb is high. InN, on the other hand, has very high side-valleys and for that reason the material is promising as a THz surface emitter.

From all the processes shown in figure 4.2, only optical phonon emission, intervalley scattering and non-radiative defect-related recombination occur on a timescale relevant to the THz emission process. The model of THz emission presented in this work uses the

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1Ref. [45]
2Ref. [46]
Figure 4.2: Typical timescales of several scattering and recombination mechanisms. Some of these affect the THz emission process.

semiclassical approach to electrical transport, and the mobility used in it (equations 2.25 and 2.30) must account only for ultrafast scattering events. This mobility is referred to as “ultrafast mobility” and is expected to be higher than the DC mobility. The ultrafast mobility is expected to be higher than the DC mobility because some scattering rates measured in the DC mobility are not accounted for in the ultrafast mobility.
5. Experimental Description

5.1 THz-TDS Setup

The THz-TDS setup that was used for this work is an optical pump-probe arrangement [4]. A commercial diode-pumped Ti:Sapphire laser delivers pulses with a duration from 80fs to 130fs, at a wavelength of 800nm. The repetition rate is 82MHz, the maximum average power is 700mW, and for this configuration the energy per laser pulse is 8nJ. The laser beam is split into a pump beam and a probe beam using an uncoated glass as beamsplitter. The power ratio is typically 95% on the pump beam and 5% on the probe beam. A schematic is shown in figure 5.1.

Emission from unbiased semiconductor surfaces is achieved by exposing the surface to the pump light beam. In order to minimize the Fresnell losses at the surface, the polarization of the pump beam is parallel to the plane of incidence. A $\lambda/2$ waveplate is used to rotate the beam’s polarization for this purpose. The pump beam is slightly focused at the semiconductor surface, and with an optical absorption length of 200nm and a laser spot size of $\approx 1mm^2$ the injected carrier density is $\approx 10^{17} cm^{-3}$. Figure 5.2 shows a sketch of the semiconductor surface emitter.

Measurements were performed setting the angle between the laser beam and the

![Figure 5.1](image_url)

Figure 5.1: Typical THz-TDS configuration. A pump-probe arrangement is used to achieve coherent detection of THz electromagnetic transients.
Figure 5.2: THz emitter based on an optically excited semiconductor surface. The laser
beam and the surface’s normal were set at the Brewster’s angle to minimize
the Fresnell losses at the semiconductor surface.

The pulsed THz radiation is detected through electro-optic sampling[47, 27] using
a \(<110>\) ZnTe crystal. Time resolution is achieved by changing the optical path length
of the probe beam with respect to the pump beam.

Electro-optic detection of THz transients is achieved when the probe beam and the
THz pulse coincide in a co-propagating geometry through a non-linear medium. ZnTe is
a non-linear material widely used for this purpose[47, 27, 48]. As the probe beam and
the THz transient propagate along the ZnTe crystal, a phase modulation is induced on
the probe beam, which depends on the THz electric field. This phase modulation on the
probe beam is analyzed with a \(\lambda/4\) waveplate and then the beam is split in two with
a Wollaston prism. At this point the phase modulation at the probe beam leads to an
intensity modulation on each of the two beams. Finally the two beams are steered into a
pair of silicon photodiodes where the modulation signal is detected on a lock-in amplifier.

The optimum condition for the electro-optic detection described above is when the
THz field and the probe beam propagate at the same velocity, that is, a perfect phase
matching condition. The strong frequency dependence of the electro-optic susceptibility[27]
limits the possibility of broadband phase matching. As the probe beam and the THz beam
travel at different velocities, dispersion of the detected signal occurs, and this decreases
the detector bandwidth. As thinner ZnTe crystals are employed, better phase matching
is achieved and a higher detection bandwidth is possible.

Next the electro-optic signal strength is discussed. If the phase matching problem
The detected signal can be approximated[48] as:

$$\frac{\Delta I}{I} \propto r \int_{0}^{l} \int_{-\infty}^{+\infty} T(\tau) E_{THz}(z, t - \tau) d\tau dz$$

Equation 5.1 is a convolution where the result comes from an “average” of the electric field magnitude over the extent of the probe pulse ($T$). It becomes evident that the bandwidth of the system is limited by the laser pulse width. Equation 5.1 also implies that the detector signal is proportional to the crystal thickness and that the detector signal is proportional to the electric field. It is noteworthy that the electric field’s polarity is preserved in this process (i.e. the sign of the electric field is carried by the detected signal).

In the electro-optic sampling, the crystal thickness is a compromise between signal strength and bandwidth. The ZnTe crystal employed in this work has a thickness of 1mm. This configuration has been found to yield a strong signal while it delivers a reasonable bandwidth. The sensitivity is highest at $\approx 1$THz, extends from 200GHz to 1.6THz at -3dB and the rolloff meets the noise floor at approximately 3THz. An optical chopper is used to modulate the pump beam, and the signal is detected with a lock-in amplifier. The combination of a coherent optical pump-probe arrangement and lock-in detection enables the system to achieve signal-noise ratios of $4 \times 10^3$ (in electric field).

### 5.2 Ultrafast Spectroscopy Setup

Transient photo-reflection has been investigated with an optical pump-probe arrangement [4]. A simplified schematic is shown in figure 5.3. The samples are excited with 130fs laser pulses with a wavelength centered at 800nm. The maximum laser pump power is 700mW. In this setup the pump beam injects a high density of photocarriers, which will change the permittivity function of the material. The probe beam is reflected from the material and small differences in the reflectivity reveal the permittivity variation. The pump and probe beams must overlap in space and in time at the semiconductor surface. They are focused by a lens ($f = 200mm$) on the sample. A 10$\mu$m pinhole was used to achieve spatial overlap of the pump and probe beams and to estimate the focal spot size. The estimated excitation density is $1.4 \times 10^{20} cm^{-3}$. All samples have been studied at room temperature.
Figure 5.3: Ultrafast spectroscopy setup. An optical pump-probe arrangement is used to perform a time-resolved measurement of the sample’s reflectivity change.

The polarization of the pump beam is parallel to the plane of incidence and perpendicular to the probe beam polarization. The purpose of this change is to avoid interference between the two beams. A $\lambda/2$ waveplate and a Glan-Thompson polarizer are used to improve the signal quality. In order to study the photo-reflection signal in dependence of the optical pump power a variable neutral density filter was used. Chopper modulation and lock-in detection were used to observe reflectivity variations ($\Delta R/R$) as low as $10^{-5}$.

Next, the semiconductor samples used in this work are described.

5.3 Te Doped GaSb Samples

GaSb is an interesting material system because recent progress in selective doping techniques [49] have enabled the growth of high purity samples with unprecedented low carrier concentration. Recent investigations of the THz emission from GaSb[22] have shown that the emission is strongly dependent on the surface field. In this work, a set of samples with a broad range of carrier concentrations have been obtained in order to study the THz emission as a function of the majority and minority carrier concentrations.

Unintentionally doped GaSb is invariably p-type in nature due to the presence of native defects such as gallium vacancies ($V_{Ga}$) and gallium antisites ($Ga_{Sb}$)[50]. In bulk GaSb, crystals grown from stoichiometric melt have a net acceptor concentration in the range of $1 - 2 \times 10^{17}cm^{-3}$ [50]. Dopants such as Te, Se and S are commonly used to grow n-type GaSb crystals. The GaSb wafers used in this study were extracted from a tellurium
(Te) compensated GaSb bulk crystal that was grown via the vertical Bridgman method. Tellurium impurities suffer segregation during the growth process, yielding an exponential concentration profile. This mechanism was used to grow a sample with an initial Te concentration in the melt such that a p- to n-type transition occurs at approximately midway along the growth axis of the ingot[51].

After the growth process, the ingot was sliced perpendicular to the growth axis to extract wafers. A total of 17 wafers were extracted from this sample. The wafers were lapped and polished to achieve a good quality surface. DC Hall mobility characterization was performed on all samples and the measured net carrier concentration and the carrier type of the wafers extracted along the growth direction are shown in figure 5.4. In the first 7 wafers (0-6), the Te level is lower than the native acceptor concentration and hence they are p-type. Wafers 7 to 16 have higher Te concentration than the native acceptor concentration and hence they are n-type. It is worth pointing out that the native acceptor concentration is considered constant along the entire length of the ingot.

5.4 GaInSb Samples

THz emission from a Ga$_{1-x}$In$_x$Sb sample is very interesting because previous investigations on the THz emission by InSb and InAs[25, 24] are still insufficient to explain why InAs is a stronger THz emitter than InSb from the photo-Dember perspective. These
investigations[24, 25] show that the THz emission from InSb is an order of magnitude lower than that of InAs. From a qualitative point of view, there is the expectation that InSb would be a more efficient THz emitter than InAs, because the bandgap of InSb is lower than that of InAs providing a higher electron temperature. Additionally the electron mobility in InSb is higher than the electron mobility in InAs. This apparent inconsistency in the photo-Dember model is explored with a Ga\textsubscript{1-x}In\textsubscript{x}Sb ingot where the bandgap and the electron mobility change uniformly from the GaSb values to the InSb values. The Ga\textsubscript{1-x}In\textsubscript{x}Sb material system is interesting because the native p-type defects in GaSb can be compensated with the native n-type defects in InSb. With this purpose, a Ga\textsubscript{1-x}In\textsubscript{x}Sb ingot (0.09 < x < 0.97) was grown by the vertical Bridgman method[52].

A part of the ingot was sliced in wafers for DC Hall characterization and the results are shown in figure 5.5. In the low indium fraction region, the carrier concentration is $1 \times 10^{17} \text{cm}^{-3}$, and the sample is p-type due to the native acceptors in GaSb. In the high indium fraction region, the carrier concentration is $3 \times 10^{16} \text{cm}^{-3}$, and the sample is n-type due to the native donors in InSb. In other regions of the ingot where 0.09 < x < 0.97, compensation occurs, and the carrier concentration is lower. The ingot has the lowest carrier concentration where the In mole fraction is about 50% and the axial position is about 15mm.

**Figure 5.5:** Electron and hole concentrations for the Ga\textsubscript{1-x}In\textsubscript{x}Sb samples (circles). The indium mole fraction (solid line) defines the carrier concentration because of native defect compensation.
Another section of the ingot was kept in one piece, where the growth direction is exposed from the region of low indium content (x=0.09) to the region of high indium content (x=0.97). This face was lapped and polished to achieve a high quality mirror-like surface. The sample was mounted in a two-dimensional translation stage so that the sample can be moved while the laser spot and the THz setup are fixed. This configuration makes it possible to scan the THz emission of a large area of the ingot. A picture is shown in figure 5.6.

5.5 InN Samples
The nitride semiconductors constitute a material system with a remarkable span of bandgaps, as shown in figure 5.7. Nitride semiconductors have been used in optoelectronic devices from the UV down to the infrared regions. However, InN has been regarded as a material that is difficult to obtain due to the lack of a straightforward growth process.

Recently, InN films with improved crystalline quality have been grown by molecular-beam epitaxy[53]. For this purpose, (0001) sapphire substrate was used. AlN and GaN buffer layers were grown on the substrate before the InN layer. Samples of several thicknesses have been analyzed in this work, ranging from 50nm to 12µm. X-ray diffraction measurements[14] have confirmed a high quality wurtzite structure.

Over the last two decades, the fundamental bandgap of InN was reported to be 2eV[54]. Recently, a much smaller value ranging from 0.7eV to 0.9eV has been reported[14].

**Figure 5.6:** GaInSb ingot in the THz-TDS setup. A translation stage allows scans along the growth direction.
Figure 5.7: Fundamental bandgap energy vs. lattice constant for different semiconductors. Nitride semiconductors have a remarkable span of bandgap energies.

The newly discovered narrow bandgap of InN suggests the application of the material as an optically excited THz emitter.

Current growth techniques produce films that have large carrier concentrations ($10^{17} - 10^{20} \text{cm}^{-3}$) and are n-type in all cases. High-resolution electron-energy-loss spectroscopy (HREELS)\cite{15} has revealed a strong surface carrier accumulation across 4nm beneath the surface. This strong carrier accumulation and its corresponding electric field are expected to enhance the THz emission process. Further, sapphire is a transparent substrate at optical frequencies and at the THz wavelength. Part of the motivation to study the THz emission from InN comes from the debate of the fundamental bandgap value for wurtzite InN. THz emission by acceleration of carriers in InN implies interband photoexcitation by photons of an energy of 1.5eV (for the Ti:Sapphire laser used in this work). This in turn implies that the fundamental bandgap of InN is lower than 1.5eV.

The THz emission from the InN samples has been investigated in two configurations: with the pump beam incident on the InN surface (fig. 5.8.a) and with the pump beam incident through the sapphire substrate on the GaN/InN interface (fig. 5.8.b). Surface carrier density is expected to be different in both configurations because the induced strain in the AlN/GaN/InN interface should not occur in the InN surface as an InN layer, several hundred nanometers thick, is fully relaxed.

A total of 31 MBE grown InN samples have been studied in this work. The carrier
concentration of these samples ranges from $4 \times 10^{17} \text{cm}^{-3}$ to $3 \times 10^{20} \text{cm}^{-3}$. This carrier concentration is obtained from DC Hall measurements. Strong evidence of surface charge accumulation suggests that the measured carrier concentration is related to the surface rather than the bulk, however, in order to compare different samples the carrier concentration was averaged over the volume of each sample. Figure 5.9 shows the mobility of unintentionally doped InN samples versus the sample thickness. It is observed that thin samples have low mobility and this suggests that the high defect density at the surface is the main contribution to scattering resulting in lower mobility. As the sample thickness increases, more carriers are transported through the bulk where the defect density is lower and therefore the total mobility is higher.

Samples have been grown with magnesium doping, silicon doping and unintentionally doped InN samples versus the sample thickness. It is observed that thin samples have low mobility and this suggests that the high defect density at the surface is the main contribution to scattering resulting in lower mobility. As the sample thickness increases, more carriers are transported through the bulk where the defect density is lower and therefore the total mobility is higher.

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**Figure 5.8:** The transparent sapphire substrate allows optical excitation from the surface side (a) and from the interface side (b)

**Figure 5.9:** Mobility of unintentionally doped InN samples vs. sample thickness.
Figure 5.10: Range of mobility (a) and carrier concentration (b) of the several samples according to the dopant.

ally doped. The ranges of mobility and carrier concentration of each group are shown in figure 5.10. Silicon doped samples have higher carrier concentration ranging from $2 \times 10^{19} \text{cm}^{-3}$ to $3 \times 10^{20} \text{cm}^{-3}$, and the mobility of the silicon doped samples was measured from $200 \text{cm}^2/\text{Vs}$ to $650 \text{cm}^2/\text{Vs}$. Magnesium doped samples have carrier concentrations ranging from $2 \times 10^{17} \text{cm}^{-3}$ to $9 \times 10^{18} \text{cm}^{-3}$, and the measured mobility ranges from $18 \text{cm}^2/\text{Vs}$ to $80 \text{cm}^2/\text{Vs}$. Finally, the unintentionally doped samples have carrier concentrations ranging from $7 \times 10^{17} \text{cm}^{-3}$ to $1 \times 10^{19} \text{cm}^{-3}$ and mobilities ranging from $400 \text{cm}^2/\text{Vs}$ to $2000 \text{cm}^2/\text{Vs}$. 
6. Experimental Results

6.1 Gallium Antimonide

Experiments performed on the GaSb sample set resulted in THz emission from all 17 GaSb samples. The temporal waveform of the THz transients exhibits the same polarity for all doping concentrations. The THz transients emitted by some of the samples are displayed in figure 6.1.a. The THz-TDS setup can resolve the electric field polarity, as is illustrated in figure 6.1.b for GaAs. In this case, different samples of opposite majority carrier type generate THz transients with opposite polarity. The fact that no polarity reversal has been observed in the GaSb samples suggests that surface field acceleration is not the only mechanism of THz emission.

The THz emission strength depends strongly on the electron and hole concentrations, as illustrated in figure 6.2.a. In this figure, the peak THz emission is plotted as a function of the sample number, which in turn defines the doping concentration. In figure 6.2.a, it is observed that the THz emission for the n-type samples (no. 7-16) is stronger than that of the p-type samples (no. 0-6). The strongest THz emission is obtained from highly compensated \( n_b \approx p_b \) GaSb samples. The n-type samples showed a significant enhancement after repolishing the GaSb surface. This strong dependence of the THz emission on the surface morphology was not observed for the p-type samples. In these experiments, optical rectification was not regarded as a possible mechanism of THz radiation from GaSb. This is because no dependence of the strength of the THz emission on the angle between the polarization of the excitation laser beam and the crystallographic orientation of the GaSb surface was observed. This dependence is characteristic of optical rectification.

The model of THz emission presented in chapter 2 is applied for this material system. The analysis is focused on two contributions; the acceleration of carriers by the surface depletion/accumulation field \([26]\) and the photo-Dember effect \([25]\). Equation 2.25 describes the radiated field resulting from surface field acceleration while equation 2.30 describes the photo-Dember radiation. The electron and hole mobilities of GaSb used in the calculation were \( \mu_e = 5000 \text{ cm}^2/\text{V s} \) and \( \mu_h = 850 \text{ cm}^2/\text{V s} \) \([37]\). Along the ingot, the native p-type concentration was assumed to be \( 4.4 \times 10^{16} \text{ cm}^{-3} \), and the Te concentration is assumed to follow \( [Te] = 2.5 \times 10^{15} \exp(x/2.51) \text{ cm}^{-3} \), where \( x \) is given in millime-
Figure 6.1: (a) THz transients from a few GaSb:Te samples. Samples W3 and W4 are p-type while samples W13 and W16 are n-type. No polarity reversal is observed. (b) THz transients generated from GaAs samples. The polarity reversal suggests that the emission mechanism is surface field acceleration.

Figure 6.2: (a) Peak THz emission vs. sample number. The photo-Dember model and the surface field model have been used to explain the dependance on majority and minority carrier concentrations. The solid line shows the calculation results, and the squares show the experimental data. (b) The carrier concentration is related to the sample number due to Te segregation.
The depletion width $W$ was calculated for all doping concentrations in our GaSb samples assuming surface potentials due to band bending of $V_s = 0.65\text{eV}$ for n-type and $V_s = 0.05\text{eV}$ for p-type GaSb\cite{31}, and a dielectric constant\cite{50} $\epsilon_s = 15.7$. The induced photocarrier concentration is estimated to be $\Delta \bar{n} \approx 1.4 \times 10^{17}\text{cm}^{-3}$.

Equations 2.20 and 2.28 describe the local electric field beneath the surface. These fields are shown in figure 6.3.b. The surface field is negative for the p-type samples and positive for the n-type GaSb samples. For n-type samples the surface field $E_s$ is much stronger than the photo-Dember field $E_D$. This is because $E_s \propto \sqrt{n_{eff}}$ and because the band bending for n-type GaSb is much stronger than for p-type GaSb. Figure 6.3 shows that in the p-type region the surface field contribution is stronger than the photo-Dember contribution. It must be kept in mind that the surface field acts across the depletion region while the photo-Dember field is present regardless of the depletion region depth. For this
reason the total photo-Dember contribution on the p-type region dominates, while the surface field contribution dominates the n-type region.

The calculation from equation 2.30 was performed with an electron temperature of $1/3k_B(h\nu - E_g)$ in order to reflect the relative magnitude of the THz-emission from the p-type and n-type samples. In previous work the hot carrier temperature was estimated to be $T_e \approx 2/3k_B(h\nu - E_g)$ for GaAs excited by 3.1eV laser radiation at room temperature[32] and $T_e \approx 1/2k_B(h\nu - E_g)$ for InP excited by 1.5eV laser radiation at 10K [13]. Recombination events are not expected in this ultrafast regime[55] but the excitation energy is larger than the intervalley scattering threshold[56] and phonon emission scattering times are expected to be around 200 fs in this doping range. We attribute the decreased electron temperature required to fit our data to these phenomena.

The surface field model predicts the highest THz emission for a compensated semiconductor where $p_b \approx n_b$. Data from figure 6.2.a confirms this as the most prominent enhancement of THz emission in GaSb. THz emission is maximized in highly compensated GaSb because under this condition the depletion width $W$ is maximized, and it is wider than the optical absorption length. Based on this comparison we conclude that in p-type GaSb, THz emission is dominated by the photo-Dember effect while surface acceleration is responsible for THz emission in highly compensated and in n-type GaSb.

The frequency spectra of the THz transients was also analyzed. In figure 6.4 the
normalized Fourier amplitudes for $f = 0.25THz$, $f = 0.7THz$ and $f = 1.5THz$ are illustrated as a function of the carrier concentration. One can observe that the n-type GaSb samples exhibit a larger THz bandwidth than the p-type GaSb samples. Although the strength of THz emission decreases for bulk electron concentrations $n_b$ larger than $\Delta \tilde{n}$, the bandwidth of the radiation does not change for this range of carrier concentrations. A strong increase of the THz bandwidth is also observed for sample no.3 for which $p_b = bn_b$. THz emission dominated by surface field acceleration has a larger bandwidth than THz emission dominated by the photo-Dember effect.
6.2 Gallium Indium Antimonide

The experiment with the Ga$_{1-x}$In$_x$Sb ingot resulted in THz emission from all scanned regions, ranging from GaSb (x=0.09) to InSb (x=0.97). Figure 6.5 shows the indium content and the THz emission amplitude as a function of the axial position (which is the position along the growth direction). The THz emission is maximum when the indium mole fraction is close to 50%. In this position the native p-type defects in GaSb compensate the native n-type defects in InSb, therefore the carrier concentration is the lowest (section 5.4).

In section 6.1 it was concluded that the THz emission from p-type GaSb (unintentionally doped) is dominated by the photo-Dember emission mechanism. Recent studies on n-type and p-type InSb[25] have shown that the THz electric field polarity from samples of opposite carrier type do not exhibit reversal, and therefore the THz emission in InSb is also attributed to the photo-Dember mechanism. Further, the surface field contribution in InSb is expected to be small because the depletion field is weak due to the narrow bandgap character of InSb[25]($E_g = 0.17 \text{ [46]}$). Some recorded THz field transients are shown in figure 6.6. In this figure we see that all transients have similar shape and similar polarity. In figure 6.1.b it was shown how the THz-TDS setup can resolve the opposite

![Figure 6.5: THz emission amplitude from the GaInSb ingot (squares) vs. axial position (growth direction). The dashed line shows the measured In fraction. THz emission amplitude is maximum where In fraction is close to 50% because native acceptors in GaSb compensate native donors in InSb.](image-url)
Figure 6.6: THz transients from the Ga$_{1-x}$In$_x$Sb ingot at different positions. There is no polarity reversal for different carrier types.

electric field polarity from the surface field of an n-type GaAs sample and a p-type GaAs sample. From the observation that no polarity reversal occurs along the entire length of the Ga$_{1-x}$In$_x$Sb ingot, it is concluded that the emission mechanism is the photo-Dember effect.

The photo-Dember model from equation 2.30 was calculated for this material system. The carrier concentration as a function of the axial position was estimated from the Hall data from extracted samples as shown in figure 6.7.b. The bandgap was estimated from the following expressions[52]:

$$E_g = 0.18x + 0.7(1 - x) - 0.415x(1 - x)$$  \hspace{1cm} (6.1)

The minority carrier concentration was calculated from the intrinsic carrier concentration. The intrinsic carrier concentration was calculated from the electron and hole effective mass according to the following expression[52]:

$$m_e^* = (0.041 - 0.0362x + 0.0092x^2) m_0$$  \hspace{1cm} (6.2)

$$m_h^* = (0.82 - 0.39x) m_0$$  \hspace{1cm} (6.3)

$$N_{c,v} = 2 \left( \frac{2\pi m_{n,p}^* k_B T}{\hbar^2} \right)^{\frac{3}{2}}$$  \hspace{1cm} (6.4)
Figure 6.7: Experimental THz field amplitude (squares) and calculated THz emission from the photo-Dember model (solid line) (a) and carrier concentration (circles) vs. axial position (b). THz emission is maximum where the carrier concentration is the lowest.

\[ n_i = \sqrt{N_c N_v} e^{-\frac{E_g}{2k_B T}} \]  

(6.5)

where \( N_c \) and \( N_v \) are the density of states in the conduction band and in the valence band respectively. The electron temperature was estimated to be \( T_e \approx 1/3k_B(h \nu - E_g) \), and the photo-injected carrier concentration is assumed to be constant and equal to \( 2.5 \times 10^{17} \text{cm}^{-3} \). The photo-injected carrier concentration is higher than the value estimated in the GaSb experiment. This is due to a smaller laser spot size. The laser spot size was reduced as an effort to increase the spatial resolution of the scan. The calculation results are shown in figure 6.7.a (solid line). The calculated electric field amplitude follows the experimental
field amplitudes (squares) well. The THz emission maximum at an axial position of about 15mm is due to the term \( \ln \left( 1 + \frac{\Delta n(1+b)}{p_b+b/n_b} \right) \) (eq. 2.30), which maximizes the radiated field at the lowest carrier concentrations. The disagreement in THz field amplitude between the photo-Dember effect calculation and the experimental data may be due to the fact that in the Ga rich region the hole carrier concentration is 4 orders of magnitude higher than the intrinsic carrier concentration, and therefore the estimation of electron carrier concentration from the intrinsic carrier concentration may be inaccurate. In the InSb region the electron carrier concentration is of the same order of magnitude as the intrinsic carrier concentration, as shown in figure 6.7.b. The intrinsic carrier concentration in the indium rich region, given by equation 6.5, is high because the bandgap of InSb (0.18eV for \( x=0.97 \) according to equation 6.1) is low, and the factor \( \exp(-E_g/2k_B T) \) is much higher than in the GaSb region. Previous qualitative analysis of the THz emission from the photo-Dember effect perspective[24, 25] suggested that narrow bandgap materials are good THz emitters because the electron temperature after optical excitation is high. Additionally, it was suggested[24, 25] that a large electron mobility and a large difference between electron mobility and hole mobility would be beneficial for the photo-Dember emission, since the space charge region is formed because the electrons are more mobile than the holes. InSb has a high electron mobility (\( \mu_e = 77000 \text{cm}^2/\text{V s} \)) and a narrow bandgap (0.17 eV). The reason why THz emission from InSb is not significantly higher than that of GaSb is that the intrinsic carrier concentration, governed by the \( \exp(-E_g/2k_B T) \) factor, increases as the bandgap decreases. This high carrier concentration has a negative effect on the THz emission process and limits the extent to which the bandgap can be reduced effectively to improve the THz emission efficiency.

Previous low temperature experiments on THz emission from InSb and InAs[24] have shown that at room temperature the THz emission from InSb is lower than InAs by an order of magnitude. As temperature decreases, THz emission from InSb increases faster than that of InAs, being InSb a stronger THz emitter than InAs at 20K. This effect was explained[24] by the proportionality between the photo-Dember field to electron mobility, and the fact that the mobility in InSb increases faster at low temperature than that of InAs. The mobility argument is insufficient to explain this effect. The reason for the enhanced emission of InSb at low temperature is that as the temperature decreases, the intrinsic carrier concentration is reduced, and this reduction has a positive effect on the photo-Dember emission mechanism. These experimental evidences bring up a
compromise between the positive effect of high electron temperature provided by narrow bandgap materials and the negative effect of a high intrinsic carrier concentration. This compromise dictates the extent to which the bandgap can be reduced in order to improve the THz emission efficiency.

6.2.1 Application Example: Interface Shape Optimization

Figure 6.8 shows the two-dimensional scan of the \( \text{Ga}_{1-x}\text{In}_x\text{Sb} \) ingot. The THz emission intensity over the entire area of the ingot has been plotted in an image. The frequency contributions lower than 1THz are plotted in red, the contributions between 1 and 2 THz are plotted in green and the contributions higher than 2THz are plotted in blue. The white points represent the strongest THz emission while the darkest points show the lowest THz emission.

It has been reported[23] that the surface field emission is strongly dependent on the surface quality of the semiconductor, while the photo-Dember effect is not. In this experiment it has been concluded that the emission is due to the photo-Dember effect and this conclusion is confirmed by the fact that the THz image does not reproduce fractures present in the ingot.

The THz emission observed depends strongly on the carrier concentration and this, in turn, is governed by the native defect density distribution. The image reveals the native defect density distribution; This is interesting because this distribution is related
to the interface shape (white region). By observing the THz emission in this manner, the interface shape can be inferred directly without interface demarcation experiments[57] such as quenching and subsequently etching the crystal.
6.3 Indium Nitride as a THz Emitter

Experiments performed with the InN samples resulted in THz emission from all of the available samples. THz emission from the InN surface and THz emission from the InN/GaN/AlN interface were observed. The THz emission from the GaN/InN interface is about an order of magnitude weaker than the THz emission from the InN surface. The time domain data is shown in figure 6.9.a.

In order to identify the THz emission mechanism, the InN samples were rotated with the growth direction as axis of rotation. The result of this experiment is shown in figure 6.9.b. Optical rectification is a process with strong dependence on the crystallographic orientation, and in figure 6.9.b there is no significant variance over different angles, as would be expected in the optical rectification process. This lack of angular dependence confirms that the THz transients are the product of photocarrier acceleration in the InN film. Further, optical rectification is not regarded as a possible mechanism of THz radiation in low bandgap materials because the optical absorption length in these materials for excitation wavelengths far above the bandgap (800nm) is short ($d \approx 208\,\text{nm}$) [58]. On the other hand, the required interaction length for optical rectification[59, 60] is:

![Figure 6.9](image-url)

**Figure 6.9:** (a) InN time-domain pulse. The THz emission from the surface is an order of magnitude higher than the THz emission from the interface. (b) The lack of angular dependence proves that optical rectification is not the THz emission mechanism.
\[ l_c = \frac{\pi c}{\omega_{THz}|n_{opt} - n_{THz}|} \]  

where \( l_c \) is the interaction length. The difference between the indexes of refraction \( n_{opt} - n_{THz} \) is in the order of unity and therefore the interaction length is in the order of the THz wavelength, which in this case is \( \sim 300 \mu m \). The optical absorption length in InN for 800nm light has been reported to be \( \approx 208 \text{nm} \)[14], which is three orders of magnitude smaller than the interaction length.

In order to evaluate whether the THz emission from InN is due to the photo-Dember effect, the emission from InN was compared to that of InAs under the same experimental conditions of optical excitation (figure 6.10.a). Although the THz electric field radiated from InAs is higher than the field radiated from InN, both values are in the same order of magnitude. THz emission from InN samples is also in the same order of magnitude as some GaSb samples used in the same experimental conditions. However, the carrier concentrations of these InAs and GaSb samples \( (n \approx 10^{16} \text{ cm}^{-3}) \) is 2 or 3 orders of magnitude lower than the carrier concentration of the InN samples \( (n \approx 10^{18} - 10^{19} \text{ cm}^{-3}) \). Equation 2.30 expresses the radiated field from the photo-Dember effect as a function of the carrier concentration. Attempts to explain the THz emission from InN by the photo-Dember effect through equation 2.30 have not been successful due to the large carrier concentration.
Figure 6.11: (a) THz emission from InN samples versus the carrier concentration. The surface field model predicts a dependence shown in dotted line. (b) Sketch of surface accumulation layer. Based on charge neutrality, we presume there is an underpopulated region behind the surface accumulation layer, across which a surface field interacts with photoinjected carriers generating THz transients.

(i.e., the photo-Dember emission from InN should be an order of magnitude lower for its carrier concentration).

Attention has been focused on the surface field THz emission model. According to this model, the magnitude of the emitted field will depend on the correlation between the optical absorption length and the surface depletion depth. It was observed that as the InN thickness is larger than the optical absorption length (200nm), the THz emission is basically independent of the thickness, as shown in figure 6.10.b.

Mahboob et al.[15] have reported HREELS data and they conclude that the surface accumulation layer is 4nm thick for a bulk carrier concentration of $3.2 \times 10^{19} \text{cm}^{-3}$. Since the optical absorption depth is $\approx 208\text{nm}$ and the accumulation layer is $\approx 4\text{nm}$, it is presumed that most of the photoinjected carriers in these experiments are absorbed beneath the surface accumulation region, and are subsequently accelerated in an “underpopulated” region. Based on charge neutrality, the existence of this “underpopulated” region is presumed. These assumptions are illustrated in figure 6.11.b. From the trend in figure 6.10.b, it is presumed that THz generation takes place over a region of the order of the optical absorption depth ($\approx 208\text{nm}$). Now the surface field acceleration model will be
applied with these assumptions. First, the underpopulated region width $w_d$ is assumed to be much larger than the accumulation layer width $w_a$:

$$w_a \ll w_d$$

and from the Gauss law the following expressions follow:

$$E_{wa} = \frac{eN_{acc}w_a}{\epsilon_s} = \frac{eN Dw_d}{\epsilon_s}$$

(6.8)

$$w_d = \frac{N_{acc}w_a}{N_D}$$

(6.9)

Substituting these equations in the surface field equation presented in equation 2.25 one can obtain:

$$E_{far} = \frac{Se^2\mu\Delta\tilde{n}}{4\pi\epsilon_0\epsilon_s e^2\tau\alpha^2} n \left[ e^{-\alpha W} + W\alpha - 1 \right]$$

(6.10)

$$E_{far} = Cn \left[ e^{-\alpha w_d} + \alpha w_d - 1 \right]$$

(6.11)

$$e^{-\alpha w_d} = 1 - \frac{\alpha w_d}{1!} + \frac{\alpha^2 w_d^2}{2!} - \frac{\alpha^3 w_d^3}{3!} + \frac{\alpha^4 w_d^4}{4!} + ...$$

(6.12)

$$E_{far} = C \left[ \frac{\alpha^2 N_{acc}^2 w_a^2}{2N_D} + \frac{\alpha^3 N_{acc}^3 w_a^3}{6N_D^2} - \frac{\alpha^4 N_{acc}^4 w_a^4}{24N_D^3} + ... \right]$$

(6.13)

This equation can be fitted from the datapoints in figure 6.11.a considering that the surface accumulation density is the same for all samples. Finally, an estimation of the surface states density is obtained:

$$\alpha N_{acc}w_a = 6.006 \times 10^{17} \text{cm}^{-3}$$

(6.14)

$$N_{acc}w_a = N_{SS} = 1.2 \times 10^{13} \text{cm}^{-2}$$

(6.15)

A surface states density $N_{SS} = 2.5 \pm 0.2 \times 10^{13} \text{cm}^{-2}$ was reported from HREELS data[15] for InN samples grown by the same laboratory than our samples. The surface states density obtained by the calculations in this thesis is in good agreement with the result from HREELS[15]. The discrepancy is explained in the following way: First our
assumption that the measured carrier concentration equals the density of donors in the bulk is ambitious, since it is known that the surface accumulation layer will affect the DC Hall measurements. Moreover, the variability in the THz emission from samples of the same carrier concentration is high, probably due to a variability in the surface density of states among the samples. Nevertheless, this result is good. It confirms that the surface field acceleration model is appropriate to explain the THz emission from InN films. By applying equation 6.9 to a sample of low carrier concentration \( n = 7 \times 10^{17} \text{cm}^{-3} \), the underpopulated layer width is found to be \( w_d = 171 \text{nm} \), which is still lower than the optical absorption depth for this material. It was shown in section 6.1 that the surface field THz emission is maximized when the depletion layer exceeds the optical absorption depth. From this it is concluded that if the carrier concentration of the InN films can be reduced by an order of magnitude, InN will surpass InAs as the most efficient semiconductor THz emitter.

Next, the relationship between THz emission and mobility is discussed. The model presented in section 2.1.1 predicts a linear dependence between the mobility (ultrafast mobility) and THz field amplitude. Figure 6.12 shows that the unintentionally doped samples follow this trend. Magnesium has been used as a p-type dopant in some samples. Carrier concentrations in InN:Mg are reduced, although the DC Hall experiment still shows these samples as n-type. THz emission from these samples is relatively high, although

![Figure 6.12: THz field amplitude vs. sample mobility. Three groups of samples are clearly identified according to their dopant.](image)
the reported mobility values are rather low. Such low mobility values are typical of compensated semiconductors, and they do not reflect the ultrafast electron mobility which is the important parameter for THz emission.

Finally, the silicon doped samples show a decreased mobility and a decreased THz emission. The reason behind this decrease is explained in the next section, and involves an increased non-radiative recombination that can reach the ultrafast regime.
6.4 Ultrafast Recombination in Doped InN

In this section, ultrafast reflectivity measurements of InN are discussed. The transient reflectivity of an optically excited semiconductor is explained by a variation of the complex refractive index through several effects, such as the absorption change due to band filling (BF), bandgap renormalization (BGR), free carrier absorption and carrier recombination. The present interpretation of the temporal evolution of the transient reflectivity of InN follows the calculations of BGR and BF as outlined in [36]. It is assumed that carriers form a hot, thermalized energy distribution during excitation itself and then cool via phonon emission. This assumption is based on the fact that measurements are performed at high excitation densities which favor quick thermalization of the hot carriers via carrier-carrier scattering and the experimental observation that InN exhibits rather long LO-phonon scattering times ($\sim$200fs)[39].

Photo-reflection transients from silicon doped InN and unintentionally doped InN are shown in figures 6.13.a and 6.13.b, respectively. For these samples, the temporal evolvement of the reflectivity signal is characterized by an initial fast decrease, followed

Figure 6.13: (a) Recorded reflectivity transient for a silicon doped InN film ($n = 10^{20} cm^{-3}$). The reflectivity decay is fitted by a single exponential ($\exp(-t/\tau)$) with $\tau = 1.19$ ps. The reflectivity decay is attributed to non-radiative defect-related recombination. (b) Reflectivity transient for an undoped InN film ($n = 7 \times 10^{18} cm^{-3}$). Two processes are observed therein: carrier cooling within the first 2 ps, and non-radiative recombination at later times.
by a quick rise and a second much slower decay of the reflectivity. In figure 6.13.b, the reflectivity change within the first 2ps or 3ps of our measurements reflects the carrier cooling. The temporal shape of the reflectivity is dominated by the interplay of BGR and BF. At short delays and high carrier temperature band filling is far from saturation and the BGR effect, which is strong in InN, dominates the reflectivity signal. This results in a decrease in reflectivity. As carriers cool and relax towards the band edge the change in absorption due to BF gets larger than the change due to BGR. This leads to an increase of the reflectivity. The subsequently observed slow decay of the reflectivity is attributed to carrier trapping and recombination. The carrier recombination lifetime was obtained from these measurements by fitting a single exponential to the reflectivity decay. The carrier lifetimes versus carrier concentration are illustrated in figure 6.15. They range from 64ps for a carrier concentration of $n = 7 \times 10^{17} \text{cm}^{-3}$ to a carrier lifetime of 680fs at $n = 4 \times 10^{20} \text{cm}^{-3}$. The overall temporal shape of the reflectivity transient is characterized by the different timescales of carrier cooling and carrier recombination. For relatively long carrier lifetimes the carrier cooling effect is clearly visible in the reflectivity transient as indicated by the initial reflectivity decrease and the broad reflectivity peak. For short carrier lifetimes the carrier cooling effect is not observed.

High speed I-V characterization[39] has shown, through power balance considerations, that the LO-phonon scattering time in InN should be around 200fs, while Raman spectroscopy[61] indicates an LO-phonon lifetime of 0.7ps to 1.3ps through uncertainty principle considerations. These values of the LO-phonon scattering time are far from those predicted by theory[62], which range from 16fs to 31fs. Although it is not possible to deduce quantitatively the LO-phonon scattering rate from the ultrafast reflectivity measurements, the overall temporal shape of the reflectivity transients supports that the LO-phonon scattering time in InN is in the range of a few hundred femtoseconds, significantly longer than the values predicted by theory.

Next, the carrier lifetime is discussed. These results demonstrate that silicon doped InN samples have recombination lifetimes lower, by an order of magnitude, than the unintentionally doped InN samples. The carrier lifetime exhibits an inverse dependence on the carrier concentration for carrier concentrations up to $4 \times 10^{20} \text{cm}^{-3}$. The reduction of the recombination lifetime in silicon doped InN compared to undoped InN suggests that silicon impurities may act as ultrafast trapping and recombination centers in InN.

The observation of an inverse relationship between carrier lifetime and carrier con-
Figure 6.14: The reflectivity change depends linearly on fluence, as expected from intraband carrier absorption. The carrier lifetime does not depend on the fluence, as expected for non-radiative recombination. The InN sample has a carrier concentration of $n = 4 \times 10^{20} \text{cm}^{-3}$.

The reflectivity change depends linearly on fluence, as expected from intraband carrier absorption. The carrier lifetime does not depend on the fluence, as expected for non-radiative recombination. The InN sample has a carrier concentration of $n = 4 \times 10^{20} \text{cm}^{-3}$. However, our time-resolved reflectivity measurements result in carrier lifetimes that are shorter by an order of magnitude. It is noteworthy that reflection experiments probe the InN surface up to the optical penetration depth (208nm at 800nm wavelength[14]) as opposed to transmission experiments where the bulk and the surface are probed. InN exhibits a high surface charge accumulation arising from surface defects. This high defect density near the surface may be responsible for the difference between reflection and transmission carrier lifetimes.

In order to investigate the nature of the carrier recombination process, reflectivity transients have been measured for various excitation fluences. The observed peak signal amplitude versus fluence as well as the carrier lifetime versus fluence are shown in figure 6.14. The reflectivity change exhibits a linear dependence on fluence. This is in agreement with intraband free carrier absorption. For this process, the change in the index of refraction is linearly proportional to the total number of carriers[63] $(\Delta n \propto (N/m_e + P/m_h))$. The carrier lifetime is independent of the fluence within the error of our measurements. This indicates that non-radiative recombination is the dominant recombination mechanism at room temperature for carrier densities up to $7 \times 10^{20} \text{cm}^{-3}$. Radiative recombination or
Figure 6.15: Recombination lifetimes versus carrier concentration. Silicon doped InN samples show recombination lifetimes lower, by an order or magnitude, than the undoped counterparts. The carrier concentration was determined by DC Hall measurements.

Auger processes are ruled out since they are expected to have quadratic or higher order dependence with the photoinjected carrier density.

The conclusion that non-radiative carrier recombination occurs in silicon doped InN samples within the timescales of the THz emission process explains the reduced efficiency of InN:Si as a THz emitter. However, sub-picosecond recombination lifetimes observed in our experiments make InN:Si an interesting candidate for possible ultrafast application such as an Auston switch[17] or similar THz photoconductive detector. InN is especially attractive for those applications because of the absence of low side-valleys[2] in this material and because the bandgap of InN is lower than that of other ultrafast photoconductive materials such as LT-GaAs. The bandgap of InN is low enough to optically inject carriers through 1.55µm optical fiber. This possibility of an InN photoconductive THz detector compatible with solid-state 1.55µm fiber lasers is very interesting for portable THz spectroscopy systems.
7. Conclusions

This dissertation presents a model for THz emission from optically excited narrow bandgap semiconductors that relates intrinsic parameters of the semiconductor, namely the majority and minority carrier concentrations and the mobilities, to the radiated THz field. The experimental approach of utilizing sets of samples where the carrier type and concentration are systematically varied is effective to study the THz emission process as a function of the carrier concentrations. Further, the conditions that enhance the THz emission process in the case of surface field acceleration and in the case of the photo-Dember effect have been clearly identified.

7.1 THz Emission Model for III-Antimonide Semiconductors

We have investigated THz radiation from a set of GaSb samples with a broad range of electron and hole concentrations. The relation between THz emission and majority and minority carrier concentration has been studied. Surface field THz emission dominates in the highly compensated region (where $p_b \approx n_b$) due to a wide depletion layer and higher surface potential in the n-type samples. In the region where $\Delta \tilde{n} \ll n_b$, THz emission decreases, however the bandwidth of the THz radiation is preserved.

It has been demonstrated that THz emission in GaSb can be enhanced by more than an order of magnitude using high purity semiconductor crystal growth and selective doping techniques. These results suggest a re-examination and possible revision of the relative THz emission strengths of different III-V semiconductors as reported previously[18].

The THz emission from Ga$_{1-x}$In$_x$Sb was explained according to the photo-Dember model. The Ga$_{1-x}$In$_x$Sb material system enabled the study of the influence of electron temperature on the THz emission process. This analysis brought up a compromise between the positive effect of high electron temperature provided by narrow bandgap materials and the negative effect of a high intrinsic carrier concentration. This compromise dictates the extent to which the bandgap can be reduced in order to improve the THz emission efficiency. This same analysis can be extended to explain why the THz emission from InSb is lower than that of InAs given the high mobility of InSb.
7.2 InN as an Emerging THz Emitter

The THz emission process from InN has been determined to be acceleration of photo-carriers by the surface electric field. This observation supports the revised value of the fundamental bandgap of InN. This material, used as a source of THz emission, exhibits comparable performance to p-type InAs, which is a well established surface THz emitter. This is a promising result considering that the MBE growth process of InN is still improving to further reduce the carrier density. From the results in this dissertation it can be predicted that if the carrier concentration of InN films can be reduced by an order of magnitude, InN will surpass InAs as the most efficient semiconductor THz emitter.

7.3 Ultrafast Recombination in Doped InN

Ultrafast reflectivity transients have been observed in InN films. Fluence dependence suggests non-radiative recombination as the source for these reflectivity changes on a femtosecond timescale. The recombination lifetime depends inversely on the defect density and on the carrier velocity. A higher defect density at the surface may explain why the lifetimes measured in this work are an order of magnitude lower than previously reported [38, 44, 64] by differential transmission measurements. The presence of silicon further reduces the carrier lifetime, and its role as a recombination center of very short lifetime is proposed. Subpicosecond recombination carrier lifetimes in silicon doped InN suggests the use of this material in ultrafast applications such as photoconductive THz detectors.
List of Publications


Conference Abstracts

- “Compensated GaSb as an improved optically excited THz emitter”,

- “InN as an emerging THz emitter”,

- “Enhanced THz Emission from Te Doped GaSb”,

- “MBE Grown InN: A Novel THz Emitter”,

- “A femtosecond laser-activated silicon reflection switch for electron-beam bunch length measurements”,

- “Pulsed terahertz emission from indium nitride thin films”,

- “Optically excited THz generation from InN thin films”,
Other Publications


Bibliography


