The partial replacement of group V atoms in III–V semiconductors with small, isoelectronic, and highly electronegative nitrogen atoms results in the formation of dilute nitrides; a class of semiconductor alloy with highly unusual electronic properties.1 Although extensive optical measurements of the large band gap bowing in III–N–Vs have been undertaken, the electronic transport properties of these materials have received little attention.2 The major factor is the profound change of the conduction band resulting from the incorporation of the nitrogen. Hence, models of electron transport employing an energy independent electron effective mass are no longer applicable.3 In this letter, we present calculations of the semiconductor statistics for InN,Sb, alloys that are shown in Fig. 1 for a range of x values calculated from the modified k·p Hamiltonian. The conduction bands found in InSb and a hypothetical InSb-like semiconductor with a constant effective mass are plotted for comparison. The parabolic dispersion relation in this figure which arises from a constant effective mass is not a valid description of the conduction band dispersion in InSb as this model ignores the interaction of the conduction band with the valence bands. The intrinsic nonparabolicity found in InSb can be described by a four band Kane model4 which results in an energy dependent effective mass. The conduction band dispersion in InN,Sb, is significantly different from that in InSb. The interaction of the nitrogen level with the conduction band causes the band gap

\[ E_M - E = \beta \sqrt{x} \]

where \( \alpha = 2.44 \text{ eV}, \beta = 1.99 \text{ eV}, \gamma = 2.47 \text{ eV}, E_N = 0.74 \text{ eV} \)

\( x \leq 0.001, 0.01, 0.02 \) The conduction band profiles for InN,Sb, are shown for 0.001 < x < 0.02. The conduction band profile for Kane band InSb and a parabolic conduction band are also plotted for comparison.
to decrease as \( x \) is increased. The conduction band also undergoes a distinct flattening as it approaches the nitrogen level, resulting in enhanced effective masses at large wave vectors.

The statistics of the electrons (that is the interdependence of the plasma frequency, \( \omega_p \), the carrier concentration, \( n \), and the effective mass at the Fermi level, \( m^*_F \)) can consequently be calculated by manipulating the \( E_\pi \) conduction band dispersion relation calculated for InN\(_{1-x}\)Sb\(_x\). This is achieved by first numerically integrating the product of the Fermi–Dirac distribution and the density of states in the conduction band to determine the concentration of conduction electrons. Further, the effective mass can be calculated as a function of Fermi level by exploiting its dependence on the curvature of the conduction band. Finally, the results of the first two calculations are then used to compute the plasma frequency, where the mass of the free carriers forming the plasma is that at the Fermi level. The result of these calculations with a range of \( x \) values for InN\(_{1-x}\)Sb\(_x\) is shown in Fig. 2 where Fig. 2(a) shows the dependence of the plasma frequency, \( \omega_p \), on the carrier concentration, \( n \), and Fig. 2(b) shows the variation of the effective mass at the Fermi level, \( m^*_F \), with the plasma frequency. These plots have been calculated for \( x = 0.001, 0.01 \), and 0.02 which corresponds to compositions with a range of band gaps from approximately that of InSb (180 meV at room temperature) to a zero band gap in InN\(_{0.02}\)Sb\(_{0.98}\), respectively. The striking result of these calculations is that for this large band gap range the statistics of the electrons show a surprisingly small variation at a given plasma frequency. Consequently, if the plasma frequency of the carriers in InN\(_{1-x}\)Sb\(_x\) can be determined then it is possible to define the concentration of carriers and their effective mass at the Fermi level within very small limits, even when the alloy composition is not known accurately. Alloy composition for dilute nitride alloys is normally determined from x-ray diffraction (XRD), since the incorporation of nitrogen substitutionally on group V sites reduces the lattice constant. However, this approach has not been possible for the InN\(_{1-x}\)Sb\(_x\) epilayers grown so far. Nonsubstitutional nitrogen has also been incorporated, causing lattice dilation which masks the usual lattice contraction, rendering the determination of the effective alloy composition by XRD impossible.

Three samples of InN\(_{1-x}\)Sb\(_x\), denoted A, B, and C, were grown on InSb buffer layers by molecular beam epitaxy with nitrogen incorporation occurring by means of an electron cyclotron resonance nitrogen plasma source. Quantification of the amount of nitrogen present in InN\(_{1-x}\)Sb\(_x\) epilayers has proved to be a major difficulty. However, this material represents the first fabrication of this alloy and several growth related issues still need to be resolved. Crucially, the InSb buffer layer, while improving growth quality, limits the accuracy of Hall measurements because of parallel conduction, thus preventing straightforward evaluation of the electron transport properties by this method. The results of the earlier calculations indicate that, if the plasma frequency can be determined, then the electron transport properties can be evaluated within small limits.

High-resolution electron-energy-loss spectroscopy (HREELS) has been employed to probe the electronic structure in the near-surface region of these InN\(_{1-x}\)Sb\(_x\) alloys. Using this technique, low-energy electrons couple to the electric fields of the surface plasmons arising from the free carriers in the conduction band resulting in electron energy loss spectra. By varying the energy of the probing electrons, the electron plasma at depths of between 100 and 1500 Å can be surveyed. A series of normalized HREEL spectra, recorded from the three samples at two different incident electron energies are shown in Fig. 3, along with dielectric theory simulations. The main feature apparent in the spectra from all three samples is the conduction band plasmon peak in the range 50–65 meV. At lower probing electron energies, a surface phonon feature at \( \approx 23 \) meV can also be observed as a shoulder on the elastic peak. Simulation of the HREEL spectra is essential in order to extract quantitative information about the system under investigation. The HREEL spectra were simulated using a two-layer model consisting of a depletion layer of thickness \( d \) and a semi-infinite bulk layer; the results of these simulations are summarized in Table I.

In addition to determining the plasma frequency of the...
TABLE I. The depletion layer thickness, plasma frequency, and plasmon lifetimes extracted from the dielectric theory simulations of the HREELS spectra and the corresponding electron transport properties for samples A, B, and C.

<table>
<thead>
<tr>
<th>Sample</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$ (Å)</td>
<td>60</td>
<td>70</td>
<td>90</td>
</tr>
<tr>
<td>$\omega_p$ (meV)</td>
<td>70±1</td>
<td>68±1</td>
<td>57±1</td>
</tr>
<tr>
<td>$\tau$ (ps)</td>
<td>0.110</td>
<td>0.068</td>
<td>0.080</td>
</tr>
<tr>
<td>$n$ ($10^{18}$ cm$^{-3}$)</td>
<td>2.15–2.26</td>
<td>2.00–2.10</td>
<td>1.22–1.30</td>
</tr>
<tr>
<td>$m^*_e/m_0$</td>
<td>0.039–0.040</td>
<td>0.038–0.039</td>
<td>0.033–0.034</td>
</tr>
<tr>
<td>$\mu$ (cm$^2$ V$^{-1}$ s$^{-1}$)</td>
<td>4800</td>
<td>3100</td>
<td>4100</td>
</tr>
</tbody>
</table>

Electrons in the conduction band, the dielectric theory simulations also enable the plasmon lifetime, $\tau$, to be found. However, this value of the plasmon lifetime provides only a lower limit for the bulk carrier lifetime because the measured plasmon lifetime is reduced by surface scattering and Landau damping.

Comparison of the plasma frequencies determined from the HREELS simulations with the semiconductor statistics calculated for a range of alloy compositions results in a narrow range of values for the carrier concentration and the effective mass at the Fermi level. Further, upon utilizing the usual definition of the electron mobility, a lower limit can be determined for this quantity by extracting plasmon lifetimes from the HREELS simulations and by using $m^*_e$ obtained from the electron statistics. The results of this analysis are also presented in Table I.

The values determined for the electron effective mass at the various Fermi levels are smaller than the effective masses at equivalent Fermi levels in InSb. This result is in marked contrast to the usual increase observed in the electron effective mass in other dilute nitride alloys; this is a consequence of the relatively shallow Fermi levels probed in this experiment where the conduction band is not undergoing the distinct flattening that gives rise to an increase in the electron effective mass. Hence, a distinct characteristic of dilute nitrides, the larger electron effective masses, only become apparent in InN$_x$Sb$_{1-x}$ when the Fermi level occupies a deeper position in energy within the conduction band where the curvature of the dispersion relation is tending towards zero. The reason for this is the extreme nonparabolicity inherent in InSb compared with the slight nonparabolicity found in GaAs.

Although the determination of the “active” nitrogen content in InN$_x$Sb$_{1-x}$ alloys grown so far is problematic, this unknown does not significantly hinder the evaluation of the electron transport properties. This is a consequence of the small variation of the electron statistics for a wide range of InN$_x$Sb$_{1-x}$ compositions at given plasma frequency. As a result, evaluating the plasma frequency and plasmon lifetime of the electrons in the conduction band of these materials enables almost complete knowledge of the electron dynamics to be ascertained. This study also demonstrates that electron effective mass enhancement only becomes apparent in InN$_x$Sb$_{1-x}$ when the Fermi level is high enough for the conduction band to be flattening as it approaches the nitrogen level.

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5. A. Lindsay (private communication).