In telecommunication systems, the use of optical means to achieve hundreds of GHz to THz signal processing rates can be more advantageous than using electrical means for two main reasons: the speed of operation using optical switching devices can be orders of magnitude higher than that of the electrical counterparts, and no electro-optical switching devices can be orders of magnitude higher than two main reasons: the speed of operation using optical to achieve hundreds of GHz to THz signal processing rates. The reduced in carrier lifetimes are attributed to Be compensation of the deep donor levels introduced by the He plasma. The carrier lifetime increases with photogenerated carrier density due to trap saturation. The FTIR results reveal sharp absorption edges in this material for doping concentrations up to \(1 \times 10^{18} \text{ cm}^{-3}\). The fast carrier dynamics and the steep absorption edge make this material very attractive for ultrafast optical switching devices for use in high-speed time-division-multiplexing fiber communication systems. © 1997 American Institute of Physics.

In a previous paper, we demonstrated that He-plasma-assisted molecular beam epitaxy and doped with various concentrations of beryllium are investigated via pump-probe experiments and Fourier transform infrared (FTIR) absorption spectroscopy. Carrier lifetimes from 10 to \(<1\) ps are obtained for samples of increasing doping concentrations. The carrier lifetime increases with photogenerated carrier density due to trap saturation. The FTIR results reveal sharp absorption edges in this material for doping concentrations up to \(1 \times 10^{18} \text{ cm}^{-3}\). The fast carrier dynamics and the steep absorption edge make this material very attractive for ultrafast optical switching devices for use in high-speed time-division-multiplexing fiber communication systems. © 1997 American Institute of Physics.

In telecommunication systems, the use of optical means to achieve hundreds of GHz to THz signal processing rates can be more advantageous than using electrical means for two main reasons: the speed of operation using optical switching devices can be orders of magnitude higher than that of the electrical counterparts, and no electro-optical conversion is needed. Optical switching devices require that the materials have simultaneously ultrafast optical response and large optical nonlinearity. Semiconductors, having large optical nonlinearities in the vicinity of their band edges, are desirable because they can easily be integrated with other devices such as laser diodes and modulators. However, the carrier lifetime of the semiconductor has to be reduced to a range of a few picoseconds to subpicoseconds for this application.

Various methods employed to reduce the carrier lifetimes of semiconductors, such as impurity doping, proton bombardment, and ion implantation, although successful in reducing carrier lifetime to picoseconds or even subpicoseconds, also cause a high level of damage to the materials which leads to high absorption or reduction of the optical nonlinearity. Low-temperature growth and subsequent annealing is another technique that has been successful in reducing the carrier lifetime of GaAs to a range from many tens of picoseconds to subpicoseconds (see, for example, Refs. 5–8). However, increased absorption is also associated with low-temperature-grown materials. Furthermore, if additional layers are to be grown at normal growth temperatures, the low-temperature layer will undergo annealing and changes in its properties associated with this.

In a previous paper, we demonstrated that He-plasma-assisted growth is a straightforward means to shorten the carrier lifetime without degrading the absorption edge and the associated large optical nonlinearity. The growth process is carried out under normal growth temperatures with the sample exposed to a continuous He-plasma stream generated by an electron cyclotron resonance (ECR) source. Subsequent layers consisting of normal materials can be grown on top of this layer by simply blocking the ECR source with a shutter. We have obtained a 15 ps lifetime in an InGaAsP sample with optical nonlinearities comparable to those of normal grown material. In this letter, we demonstrate that by combining He-plasma-assisted growth with Be doping the carrier lifetime can be further reduced to subpicoseconds. With moderate doping concentrations, a relatively sharp absorption edge is maintained. Also investigated is the carrier lifetime dependency on the initial photogenerated carrier density in doped and undoped samples. A qualitative explanation for the role of He plasma and Be in reducing the carrier lifetime is presented.

Five 2-µm-thick InGaAsP samples grown on lattice-matched InP substrates were investigated and compared in this work. Sample 1 (standard InGaAsP) was grown at 435 °C by gas source molecular beam epitaxy; sample 2 was grown under similar conditions but with the He plasma on; samples 3, 4, and 5 were all grown with the He plasma on and were doped with increasing Be concentrations of \(3 \times 10^{17}\), \(1 \times 10^{18}\), and \(6 \times 10^{18} \text{ cm}^{-3}\), respectively.

Standard pump-probe techniques were used to obtain the dynamics of absorption saturation and its subsequent recovery, as shown in Fig. 1, from which carrier lifetimes for samples 2–5 were inferred. Both the pump and probe consist of 1 ps transform-limited pulses at 1.50 µm generated by a tunable optical parametric oscillator. They are focused onto the sample to a spot size 35 μm in diameter. The pump pulse energy used for Fig. 1 is 130 pJ and the pump-probe energy ratio is 100. The carrier density generated by the pump pulse is approximately \(1.5 \times 10^{17} \text{ cm}^{-3}\) for all four samples. Because of the large difference in the density of states of the conduction and valence bands, the transient absorption is
The carrier lifetime was also studied as a function of the photogenerated carrier density for doped and undoped samples by varying the pump pulse energy. The results for sample 2 (undoped) and sample 4 ($1 \times 10^{18}$ cm$^{-3}$ doping) are illustrated in Figs. 2(a) and 2(b), respectively. The general behavior for the two samples is the same: as the photogenerated carrier density decreases, the carrier lifetime decreases. At a certain carrier density (lower for the undoped sample and higher for the doped sample), the absorption recovery transient crosses over the equilibrium level and results in a negative tail of transmission change. This provides another indication that, when the generated carrier density is higher than the electron trap concentration, the absorption recovery is limited by the relatively slow recombination time; on the other hand, when the generated carrier density is lower, the initial absorption recovery is fast, as characterized by the fast electron trapping time. Since there are many more unoccupied traps in the doped sample than in the undoped sample (due to Be compensation), the carrier density where the crossover occurs is higher for the doped sample than for the undoped one.

For the material to be useful for optical switching devices, fast carrier lifetime should also be accompanied by a sharp absorption band edge. The absorption near the band edge of the five samples obtained by FTIR measurements is shown for comparison in Fig. 3. There is little difference in the slope of the band edge between sample 1 (standard), sample 2 (He plasma, undoped), or sample 3 (He plasma, with $3 \times 10^{17}$ cm$^{-3}$ Be doping). In fact, at $3 \times 10^{17}$ cm$^{-3}$ doping concentration, the absorption edge is essentially iden-
lifetime increases with photogenerated carrier density due to the He plasma. We have also shown that the carrier doping is due to compensation of deep donor levels introduced by the He plasma. We believe that the reduction in absorption recovery time by Be doping is due to compensation of deep donor levels introduced by the He plasma. We have also shown that the carrier lifetime increases with photogenerated carrier density due to the limited number of traps. The sharp absorption edge is preserved in this material with doping concentrations up to $1 \times 10^{18}$ cm$^{-3}$. The fast carrier lifetime and the steep absorption edge make this material very promising for ultrafast optical switching applications.

This work is funded by the Ontario Laser and Lightwave Research Centre, the Ontario Centre for Materials Research, and the Natural Science and Engineering Research Council of Canada.

1 See, for example, P. W. Smith, IEEE International Conference on Communications, June 1987 p. 1570.