Extended Abstracts of the 2003 International Conference on Solid State Devices and Materials, Tokyo, 2003, pp. 184-185

A-5-3

Solid-State Optical Routing Device Utilizing Minority Carrier Drift

Hironori Tsukamoto, Thomas D. Boone and Jerry M. Woodall

Yale University, Department of Electrical Engineering
15 Prospect Street, New Haven, CT 06520, U.S.A.
Phone: 1-(203)432-4304 Fax:1-(203)432-6420 E-mail: hironori.tsukamoto@yale.edu

1. Introduction

Optical-signal-routing is a key technology to enhance the flexibility of optical information system. While recent research advances in photonic bandgap crystals [1-3] and micro-electromechanical systems (MEMS) [4] provide a possible approach to realizing such systems, another concept for a routing device would be desired when operation on a timescale of a few-nanoseconds is needed in a dynamic optical routing system. Here we propose a novel concept of solid-state optical signal routing devices utilizing minority-carrier-drift in semiconductors [5,6]. The concept is to spatially shift minority carriers generated by an input optical signal with electric fields before they recombine with majority carriers, so that positioning of photon emission from recombination is possible. We show a feasibility of a few-nanoseconds solid-state optical routing devices for the first time through observation of lateral drift of electrons in p-GaAs.

2. Concept for Solid-State Optical Routing Devices

A schematic illustration of a four-channel solid-state optical routing (SSOR) device is shown in Fig. 1. This figure shows that an optical fiber is located on the center of the channel and provides optical modulation signals as an input signal source. The optical input signals generate minority carriers in the channel and the carriers are drifted toward channel *A* with an electric field between pad *A* and *C*. The minority carries recombine with majority carriers after drifting and emit photons in channel *A* region. Since an optical fiber is located on the channel *A*, PL emission in the channel *A* is probed with the fiber as the output signals. For a wavelength of the input signal, an appropriate direct bandgap material is chosen as a channel layer in order to effectively absorb the input light and generate PL emission. When a material with minority carrier radiative lifetime of τ_r ~2 ns and a mobility μ is used for the channel, for example, the average displacement x from the input spot is obtained by $x = \mu E \tau_r$ under an electric field E. For a minority carrier mobility of μ ~2000 cm^2/V-s and an electric field of E = 2 kV/cm, we can expect to achieve a displacement of PL emission from the input spot to be x = 80 (μm). This value could be enough to put another optical fiber to probe the output PL signal. The approximate time delay of the signal is obtained by $d/\mu E$ for a distance d between the input and output fibers. Therefore it would be possible to realize a multi-channel SSOR device if a device pattern with plural electrodes were designed.

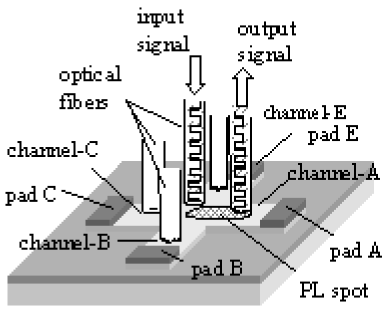

Fig. 1 A conceptual illustration of a four-channel SSOR device. An optical input signal is routed to channel *A* by applying a DC bias between the electrode pad *A* and *C*.

3. Fundamental Experiments for SSOR devices

3.1 Sample structure

A high quality heterostructure is needed to provide higher minority carrier mobility and efficient radiative recombination in the channel layer. p-type modulation doped heterostructures were designed for the purpose.

p-GaAs(10nm)/p-$Al_{0.5}Ga_{0.5}$As(50nm)/p-$Al_{0.9}Ga_{0.1}$As(25 nm)/undopedGaAs(100nm)/p-$Al_{0.9}Ga_{0.1}$As(50nm) layers were grown on semi-insulating GaAs (001) substrate. The top GaAs layer and three AlGaAs layers were doped with beryllium (Be) atoms at 2×10^{19} cm^{-3}, which was designed to provide a high density of free holes in the undoped GaAs channel layer to be approximately $1\text{x}10^{18}$cm^{-3} and allows a high electron mobility in the channel layer. The GaAs capping layer is for reducing oxidation of the sample surface. The band diagram of the structure at equilibrium is shown in Fig. 2. The $Al_{0.9}Ga_{0.1}$As barrier layers are

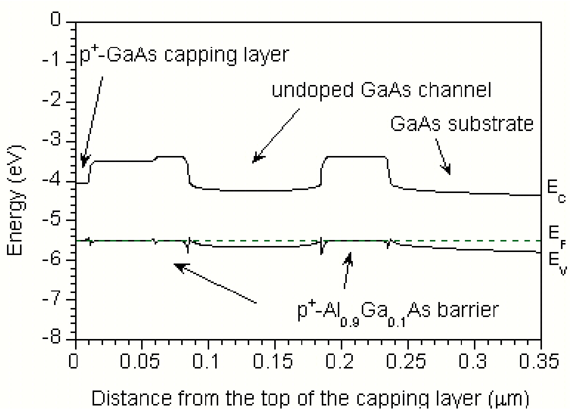

Fig. 2. A schematic band diagram of the sample structure.

employed to confine photo-generated electrons in the channel layer by forming a conduction band offset for the GaAs channel layer. Bar shape mesa is formed and etched down to the substrate with photolithography and chemical etching process. Two Ti/Au non-alloyed electrical contacts were formed on the top of the mesa with a spacing of 220 μm. The minority carrier (electron) radiative lifetime τ_r of the GaAs channel layer measured with time resolved photoluminescence is 4.18 ns at room temperature.

3.2 Measurement of PL spot displacement under DC bias

A schematic diagram of the experimental setup is shown in Fig. 3, which is designed to visualize PL emission from samples and measure the minority carrier drift in the electric fields. A diode laser is focused onto the surface of a mesa-etched bar with a couple of electrodes for photo-pumping of electron-hole pairs (ϕ< 100 μm, λ = 660 nm, P~1 mW). Most photons of the laser are absorbed in the channel layer. DC bias of ±20V is applied to the probes. A charge-coupled device (CCD) camera is mounted on an optical microscope with a colored glass filter to observe the infrared PL emission from the channel layer as spatial minority carrier distribution, which is set with an oblique angle.

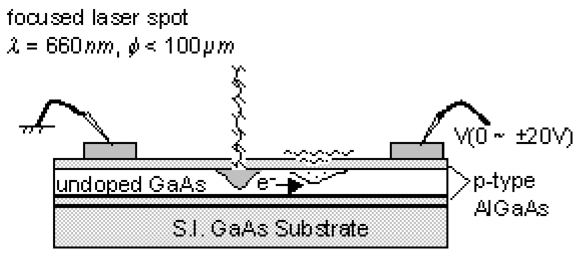

Fig. 3. An experimental setup to investigate the feasibility of optical routing devices by using electrons. DC biases are applied

Photographs of PL emission from a sample with and without DC bias are shown in Fig. 4, indicating applied biases (left probe: ground). At room temperature, a bright PL spot is seen between the two probes, showing a round shape with a 100 μm diameter at zero bias, as shown in Fig. 4 (a). The bright spot indicates that the material quality grown and the structure designed are good enough for reduction of nonradiative recombination in the channel layer. The typical peak wavelength measured is 871 nm. When DC bias is applied to the probes, the spot moves toward the positively biased probe (right side) and the displacement from the original spot increases with the applied bias, as shown in Figs. 4 (b) and 4 (c). This indicates that the photo-generated minority carriers are electrons, since the PL spot drifts toward the positively biased probe. Therefore the concept of minority carrier lateral drift before the recombination is confirmed. It is also seen that the maximum displacement of PL spot at 20 V is longer than 100 μm from the original spot. This distance is long enough to put a single or multi-mode optical fiber as

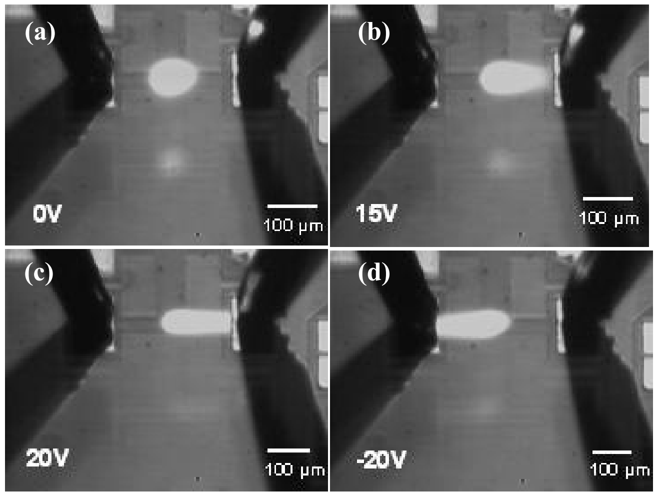

Fig. 4. Photographs of a photo-generated sample with and without DC bias. PL spot moves with dc biases.

an output signal probe. Assuming that the radiative lifetime of the electrons in the channel layer is constant (τ_r = 4 ns), the electron drift velocity is calculated to be 2.5x10^6 cm/s. When a reverse bias (-20V) was applied to the electrodes, the PL spot is immediately swept out toward the left side as shown in Fig. 4(d). When a drive-circuit with gigahertz operation is used for the present device, nanoseconds dynamic routing would be possible. The two-channel optical routing device demonstrated here could be applied for a multi-channel solid-state optical routing device when a radial bar pattern with symmetrical contacts were used. As the present device operates with non-selection of wavelength, this device would be suitable for the signal routing at the end stage of the wavelength division multiplexing (WDM) system for short distance communication. The modulation signal distributed by the present technique can be potentially degraded with the minority carrier diffusion in a channel during lateral drift and the theoretical analysis is under investigation.

4. Conclusions

A novel concept for solid-state optical routing devices utilizing minority carrier drift was proposed. The output PL emission shift as a function of electric field showed the feasibility of the concept and its potential limitation was indicated.

Acknowledgements

The authors would like to thank Louise H. Grober for the MBE structure growth, Robert Koudelka for the TRPL measurements, Prof. Jung Han for fruitful discussions and Takashi Tamagawa for useful suggestions.

References

[1] E. Yablonovitch, Phys. Rev. Lett. **58** (1987) 2059.
[2] S. John, Phys. Rev. Lett. **58** (1987) 2486.
[3] Y. A. Vlasov et al., Nature **414** (2001) 289.
[4] L. Y. Lin et al., IEEE Photon. Technol. Lett. **10** (1998) 1425.
[5] J. R. Haynes et al., Phys. Rev. **81** (1951) 835.
[6] T. D. Boone et al., To be published in Appl. Phys. Lett. (May issue).