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A Novel Material of GaInNAs for Long-Wavelength-Range Laser Diodes with Excellent High-Temperature Performance

M. Kondow, K. Uomi, A. Niwa, T. Kitatani, S. Watahiki, and Y. Yazawa

Central Research Laboratory, Hitachi, Ltd.,
1-280 Higashi-Koigakubo, Kokubunji-shi, Tokyo 185, Japan
Phone: +81-423-23-1111; Fax: +81-423-27-7786; E-mail: kondow@crl.hitachi.co.jp

We propose a novel material, GaInNAs/GaAs, to drastically improve the temperature characteristics (T_0) in long-wavelength-range laser diodes. The feasibility of our proposal is experimentally demonstrated.

1. Introduction

In present optical fiber communications, laser diodes are used in the 1.3 or 1.55 μm wavelength ranges due to the optical fiber windows. They consist of GaInPAs alloy semiconductors that can be formed on an InP substrate. Since the GaInPAs/InP laser diodes have poor temperature characteristics (T_0), thermoelectric coolers are required in practical use. Therefore uncooled laser diodes that can perform well in a high temperature environment are quite desired. The T_0 was recently improved from 60 to 80 K by using AlGaInAs alloy semiconductor formed on an InP substrate.[1] However, this T_0 is still much less than that of GaInAs/GaAs lasers (λ: 0.98 μm), i.e., over 150 K. The low T_0 is mainly due to poor electron confinement.

In this work, we propose a novel material: GaInNAs. It can be formed on a GaAs substrate, and has a bandgap energy in the long-wavelength-range. Combining GaInNAs with wide gap materials such as AlGaAs that are formed on a GaAs substrate provides perfect electron confinement so that the T_0 in long-wavelength-range laser diodes will be drastically improved.

2. Bandgap and band lineup of GaInNAs

Figure 1 shows the relationship between the lattice constant and bandgap energy in III-V alloy semiconductors including novel materials of GaNAs and GaInNAs. Data of GaNAs were derived from our experimental results.[2] Adding In to GaAs, i.e., making the GaInAs alloy semiconductor, increases the lattice constant, while adding N to GaAs, i.e., making the GaNAs alloy semiconductor, decreases the lattice constant. GaInNAs can therefore be lattice matched to GaAs by adjusting the In and N

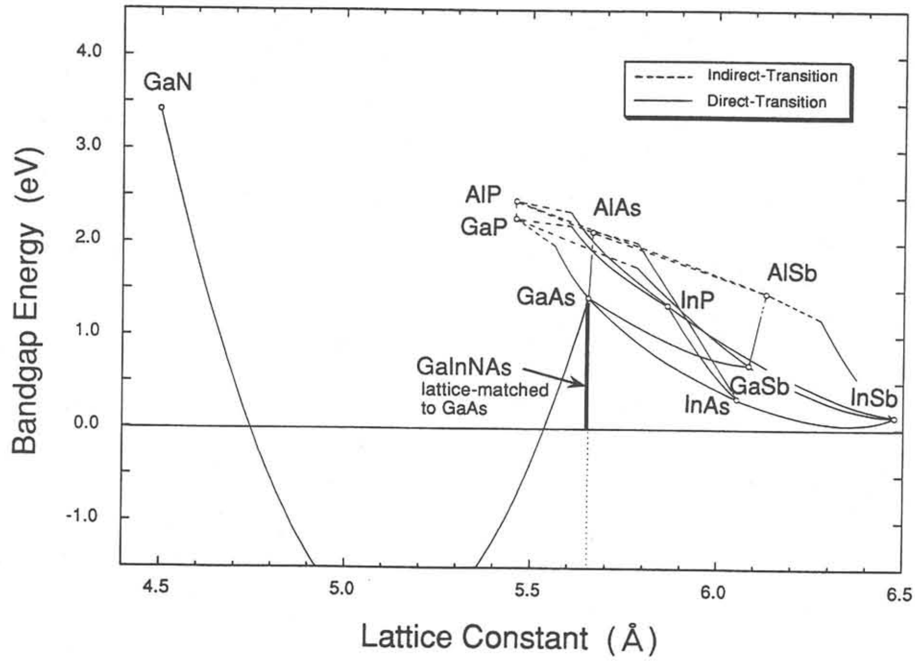

Figure 1 Relationship between the lattice constant and bandgap energy in III-V alloy semiconductors.

contents. Adding In to GaAs decreases the bandgap. In the same way, adding N to GaAs decreases the bandgap as is shown in Fig. 1. Note that this is the opposite dependence to a conventional alloy semiconductor of GaPAs. Since GaInAs and GaNAs are both direct-transition-type semiconductors, GaInNAs is thought to be a light-emitting material and to have a bandgap energy suitable for long-wavelength-range laser diodes.

Next, band lineup is discussed. Applying a material in the quantum well active layer of laser diodes, type I band lineup is essential to confine both electrons and holes in the quantum well layer. A schematic diagram of band lineup for GaInAs is shown in the right part of Fig. 2. Band lineup of GaNAs is shown in the left part of the figure. Data of GaNAs were derived from the theoretical calculation by Sakai et al.[3] The horizontal axis was coordinated in strain to draw these diagrams in the same figure. Increasing the In content in GaInAs, i.e., increasing the compressive strain, lowers the conduction band and raises the valence band. On the other hand, increasing the N content in GaNAs, i.e., increasing the tensile strain, lowers both the conduction and valence bands. Since the decreasing rate of the conduction band is larger than that of the valence band, increasing the N content decreases the bandgap. Suppose N is added to GaInAs to form GaInNAs, the conduction and valence bands will be moved from A to B and from D to E in Fig. 2, respectively. At the alloy composition in which the GaInNAs is lattice matched to GaAs, i.e., non-strain, the conduction and valence bands will be located at C and F, respectively. Note that the valence bands of the GaInNAs and GaAs are on the same energy level. Therefore, combining GaInNAs with wide gap materials such as AlGaAs, type I band lineup is easily achieved. In addition, when GaInNAs is combined with GaAs, the GaInNAs has to be compressively strained to obtain the type I hetero-interfaces, and should be grown as a quantum well layer that is thinner than the critical thickness at which misfit dislocations are generated.

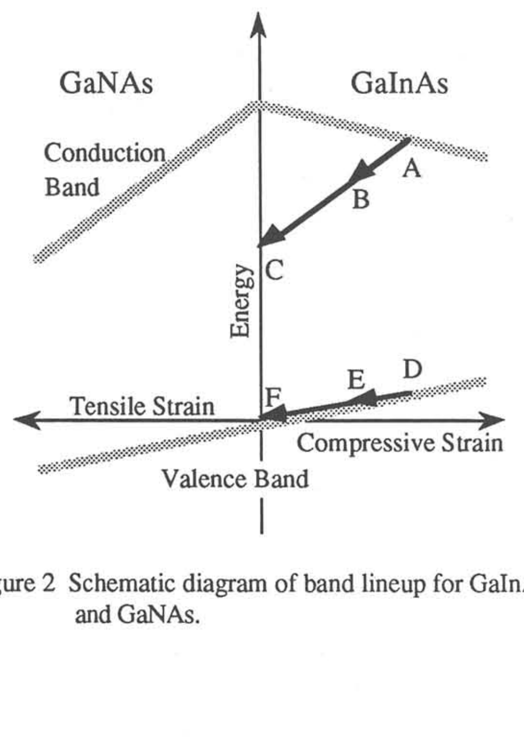

Figure 2 Schematic diagram of band lineup for GaInAs and GaNAs.

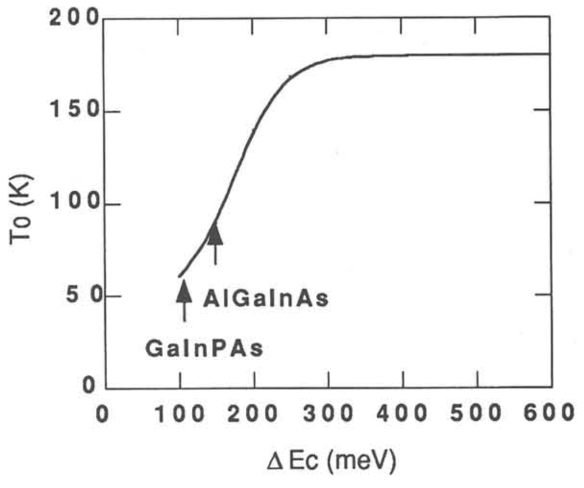

Figure 3 Calculated relationship between the T_0 and ΔEc.

3. Calculated temperature characteristics of GaInNAs laser diodes

Figure 3 shows the calculated T_0 as a function of band discontinuity energy in the conduction band (ΔEc) of the quantum well active layer. The calculation is based on the thermionic emission model by Suemune et al.[4] When the quantum well is so deep that electrons are not overflowed to the barrier layer, T_0 is assumed to be 180 K , i.e., the intrinsic value for laser diode. The return rate of overflowed electron to the active layer is estimated by fitting to the experimental T_0 of conventional GaInPAs/InP and AlGaInAs/InP laser diodes. What Fig. 3 implies is the fact that a ΔEc larger than 300 meV perfectly prevents electron from overflowing and that T_0 becomes the intrinsic value for laser diode.

Figure 4 shows band lineup of materials with a wavelength in 1.3 μm range. As shown in Fig. 4 (a), a conventional GaInPAs alloy semiconductor has a small ΔEc and a large band discontinuity energy in valence band (ΔEv). The ΔEv of 150 meV is too large for holes with heavy mass. On the other hand, GaInNAs has ideal band lineup, as shown in Fig. 4 (b). The ΔEc of 570 meV is quite sufficient to prevent the electron overflow, as discussed above. Therefore, uncooled laser diodes that perform well in a high temperature environment can be expected by employing a novel material of GaInNAs.

4. Experimental

Finally, we show briefly some results of our primary experiment. The GaInNAs was grown by using gas-source molecular beam epitaxy in which a nitrogen radical

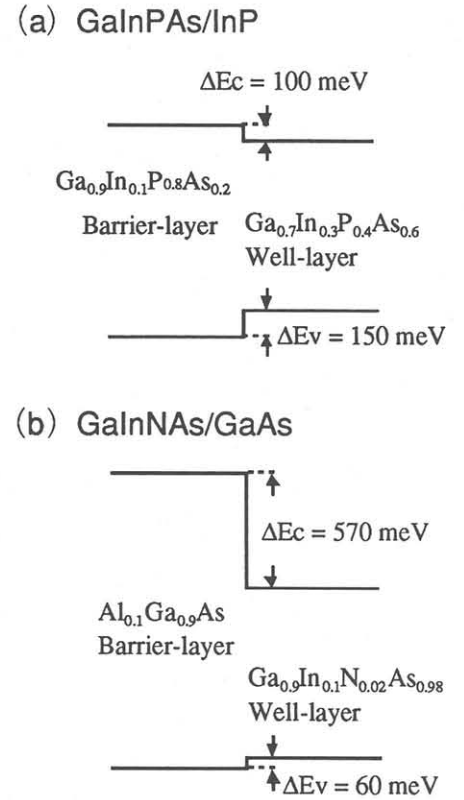

Figure 4 Band lineup of materials with a wavelength in the 1.3 μm range.

was used as the nitrogen source. This method was based on our proposed growth method for GaNAs.[2)] Metal Ga, metal In, arsine gas, and nitrogen gas were used as precursors. The Ga and In flux was derived from a conventional thermal effusion cell. The As_2 flux was obtained by cracking arsine at 900°C. The N-radical flux was produced by rf discharge in the radical cell. The

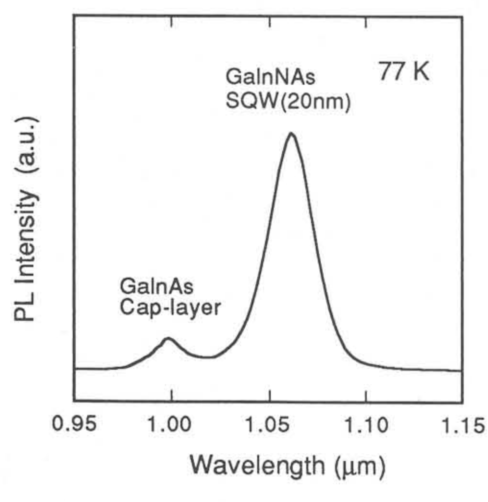

Figure 5 Photoluminescence spectra of GaInNAs and GaInAs.

substrate was (100)-oriented Si-doped n-type GaAs. After thermal cleaning of the substrate surface at 580 °C, the epitaxial layer was grown at 500 °C. The surface morphology of the GaInNAs epitaxial layers was smooth and mirror-like, just like a GaAs homo-epitaxial layer. Details in crystal growth of GaInNAs will be separately reported elsewhere.

The photoluminescence (PL) spectra of $Ga_{0.8}In_{0.2}N_{0.005}As_{0.995}$ and $Ga_{0.8}In_{0.2}As$ having the same In content are shown in Fig. 5. Adding N to the GaInAs decreases the PL peak energy by 75 meV. This shift is close to the energy shift between GaAs and $GaN_{0.005}As_{0.995}$ in which the N content is the same as the above GaInNAs sample. The bandgap of GaInNAs thus decreases with increasing N content in the same way as in GaNAs, as expected. Although the PL peak energy shown in Fig. 5 is not located in the long-wavelength-range, GaInNAs with a bandgap in long-wavelength-range may be easily obtained by increasing the N content. This is because the successful growth of GaNAs with N content up to 10% has been reported.[5)]

5. Conclusion

In conclusion, we propose a novel material: GaInNAs. It can be formed on a GaAs substrate, and has a bandgap energy suitable for the long-wavelength-range. Combining GaInNAs with wide gap materials such as AlGaAs that can be formed on a GaAs substrate provides type I hetero-interfaces. Band lineup will be ideal to prevent carrier overflow. Therefore, applying GaInNAs to long-wavelength-range laser diodes is expected to result in excellent high-temperature performance. The feasibility of our proposal is experimentally demonstrated.

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