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# Fabrication and characterization of a periodically-inverted AlGaAs double-heterostructure p-i-n diode

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**Abstract**

**We have fabricated a periodically-inverted AlGaAs double-heterostructure p-i-n diode as a wavelength conversion device utilizing current-induced optical gain. Electroluminescence of the diode was observed at 0.775 µm, which was ideal for obtaining the gain at the pump wavelength in difference-frequency generation for optical communication applications.**

## 1. Introduction

Difference frequency generation (DFG) (interaction wavelengths: 0.775 µm for a pump wave; 1.55 µm bands for signal/idler waves) is expected to play a crucial role for highly-reliable optical communication devices. AlGaAs is a promising material for the DFG devices because of its large nonlinear coefficients and the possibility of current injection to utilize optical gain by stimulated emission due to interband transition. The introduction of current injection in AlGaAs wavelength conversion devices will lead to not only compensation of relatively high propagation losses, but also to extreme increase of conversion efficiencies. To achieve high conversion efficiencies, it is necessary to fabricate waveguide structure and periodically-inverted structure which is needed to achieve quasi phase matching. We have fabricated periodically-inverted GaAs/AlGaAs double-heterostructure p-i-n diodes [1], and observed electroluminescence (EL) from the fabricated diode, whose peak wavelength is 0.86 µm (1.42 eV) corresponding to the interband transition of GaAs. In this paper, we report fabrication and characterization of a periodically-inverted AlGaAs double-heterostructure p-i-n diode with an $Al_{0.145}Ga_{0.855}As$ core layer which enables us to obtain optical gain at 0.775 µm, a pump wavelength for DFG in the optical communication bands.

## 2. Experimental and discussion

We fabricated a periodically-inverted AlGaAs double-heterostructure p-i-n diode schematically shown in Fig. 1. Details of the AlGaAs p-i-n diode structure are summarized in Table 1. We prepared the diode as follows; 1) a spatially inverted n-GaAs layer was grown on an n-GaAs (100) substrate by using sublattice reversal epitaxy [2] based on molecular beam epitaxy (MBE); 2) The spatially inverted substrate was periodically etched with photoresist stripes running along [0$\bar{1}$1] with a period of 10 µm so that non-inverted and inverted n-GaAs were exposed alternatively by using wet etching process; 3) a periodically-inverted n-GaAs layer was grown by using MBE; 4) The surface was flattened by using chemical mechanical polishing (CMP); 5) an AlGaAs double-heterostructure p-i-n diode was grown on the CMP surface with MBE; 6) ridges propagating along [011] direction were formed on the p-side surface of the grown p-i-n diode by using photolithography and wet etching; 7) $CaF_2$ was fabricated on the surface as an insulation layer for current constriction using vacuum evaporation and patterning by lift-off process; 8) electrodes were evaporated on each surface of the diode.

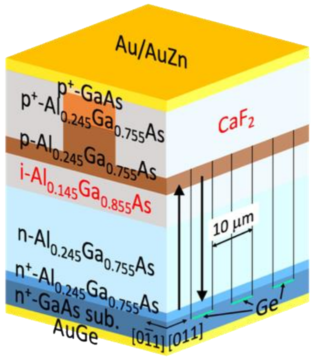


Fig. 1 Schematic of a periodically-inverted AlGaAs double-heterostuctutre p-i-n diode.

Table 1. Details of the diode structure

| Layer | Thickness (nm) | Dopant | Concentration ($cm^{-3}$) |
|---|---|---|---|
| $p^+$-GaAs | 100 | Be | $1.0\times10^{18}$ |
| $p^+$-$Al_{0.245}Ga_{0.755}As$ | 200 | Be | $1.0\times10^{18}$ |
| p-$Al_{0.245}Ga_{0.755}As$ | 800 | Be | $1.0\times10^{17}$ |
| i-$Al_{0.145}Ga_{0.855}As$ | 700 | Si | $5.0\times10^{15}$ |
| n-$Al_{0.245}Ga_{0.755}As$ | 5000 | Si | $1.0\times10^{17}$ |
| $n^+$-$Al_{0.245}Ga_{0.755}As$ | 200 | Si | $1.0\times10^{18}$ |
| $n^+$-GaAs | 1500 | Si | $1.0\times10^{18}$ |
| n-Ge | 30 | | |

Figure 2 (a) shows a cross-sectional SEM image of the stain-etched (0$\bar{1}$1) edge of the device. Although the boundaries between inverted and non-inverted domains are slightly tilted, periodically-inverted and waveguide structures are successfully fabricated with a period of 10 µm. A cross-sectional SEM image taken from [011] direction is shown in Fig. 2 (b). Since the Au/AnZn electrode mostly contacts with the surface of $p^+$-layer of the diode, the optical and carrier confinements are expected.

We characterized diode performance of the fabricated device. A current-voltage curve measured under dark condition

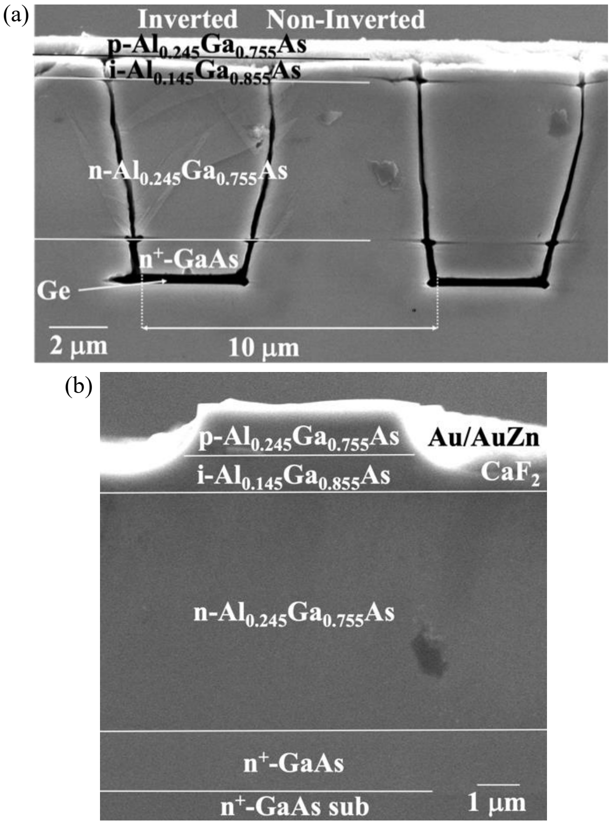


Fig. 2 Cross-sectional SEM images of the fabricated device taken from (a) stain-etched [0$\bar{1}$1] facet and (b) from [011] edge.

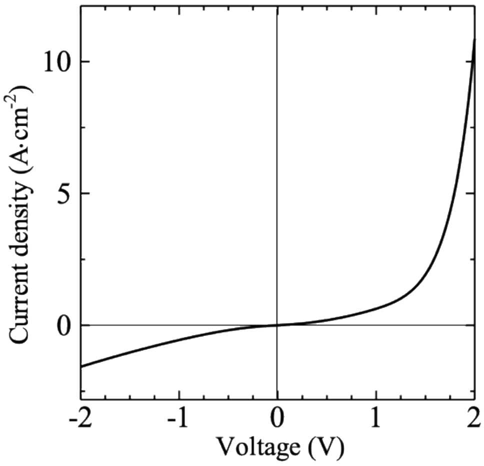


Fig. 3 Current density-voltage curve of the fabricated device under dark condition.

is shown in Fig. 3. The obtained curve indicates diode characteristic, although relatively large leak current, probably due to electrode contact to the i-layer shown in Fig. 2(b), was observed. The ideal factor of the device, 10.4, is as twice as that of a periodically-inverted GaAs/AlGaAs diode [1].

Figure 4 shows the EL spectrum of the device observed from the (011) facet at 20°C with a current density of 250 A/cm$^2$. The peak energy (wavelength) of the spectrum was 1.60 eV (775 nm) as expected. The EL linewidth, 60 meV, is slightly broadened as spontaneous emission through $Al_{0.145}Ga_{0.855}As$ interband transition. The broadening may be

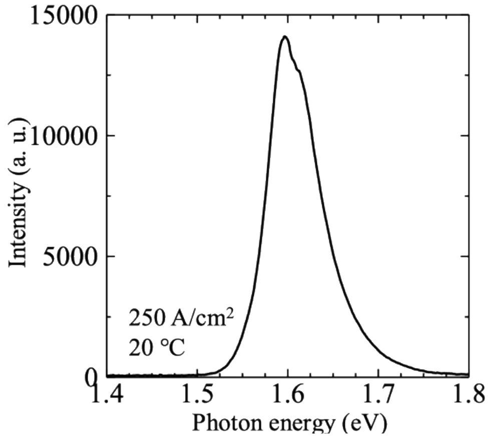


Fig. 4 EL spectrum of the fabricated device.

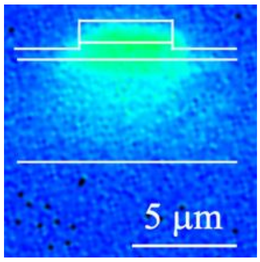


Fig. 5 EL distribution of the fabricated device at 20°C

caused by periodic modulation of Al composition owing to difference between surface diffusion lengths of Ga and Al in the AlGaAs MBE growth process [3]. Figure 5 represents the spatial distribution of the edge-emitting EL observed from [011] direction of the device. The obtained near-field pattern is similar to the fundamental waveguiding mode. This clearly shows that EL is confined into the waveguide and the introduced current constriction structure works well as expected.

In order to control the tilted boundaries and to reduce the leak current, we have to improve the fabrication process by optimizing the growth condition (such as a V/III ratio), and by introducing anisotropic dry etching process to suppress the undercut during ridge fabrication.

## 3. Conclusions

We have fabricated a periodically-inverted AlGaAs double-heterostructure p-i-n diode and observed waveguiding and edge-emitting EL with a peak energy 1.60 eV (775 nm). This result will be an important milestone for current-injected AlGaAs wavelength conversion devices toward realizing highly efficient of DFG in optical communication wavelengths.

## References

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