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Anti-Phase Direct Bonding of InP and GaAs and Its Application to Semiconductor Lasers

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We propose anti-phase direct bonding of lattice-mismatched materials, and report on the first demonstration of its application to device fabrication. Anti-phase direct bonding is a way to obtain a structure in which the lattice order is symmetric at the bonding interface. Two wafers bonded at the atomic level and the misfit dislocations were localized at the bonding interface, as well as showed for in-phase direct bonding in which the lattice order is equivalent to that of a structure obtained by heteroepitaxy. These two types of direct bonding were applied to fabricate 1.55-μm InP-based MQW lasers on GaAs. Although the lasers formed by anti-phase direct bonding suffer some performance deterioration such as lower slope efficiency, their level of performance was only slightly lower than those formed by in-phase direct bonding. Moreover, stable operation was possible for more than 1000 hours at 50°C.

I. INTRODUCTION

The fabrication of III-V compounds on highly lattice-mismatched substrates has been widely studied with a view to developing specific devices such as opto-electronic integrated circuits. For this aim, heteroepitaxy such as GaAs-on-Si, InP-on-Si, and InP-on-GaAs has been viewed as the key technology[1]. However, it is difficult to get rid of the high density of threading dislocations in hetero-epitaxially grown layers. Therefore, device fabrication based on this technique has not been realized sufficiently.

On the other hand, direct bonding has recently been reported as a promising technique for such application. One superior feature is that misfit dislocations can be localized at the bonding interface, which enables us to eliminate threading dislocations in the fabricated layers. Up to now, fabrication of InP-based long-wavelength lasers on GaAs has been achieved without degrading the performance below that of lasers fabricated on InP by homoepitaxy[2,3]. Fabrication of a GaAs-based laser on Si substrate has also been reported[4]. In addition, direct bonding has been applied to fabricate long-wavelength surface emitting lasers on GaAs-based highly reflective mirrors[5]. Although there are some problems related to this technique, such as high resistance at the bonding interface or increasing substrate costs, it is very attractive as a way remove a high density of threading dislocations, which has long been a major problem in heteroepitaxy.

In addition to this superior feature, there is a possibility of fabricating devices with various relations of crystallographic axes between the device and the substrate. If this is possible, monolithic device integration will be less restricted, thus allowing for more innovative types of integration. In this paper, we propose anti-phase direct bonding between lattice-mismatched materials, in which the lattice structure is symmetric at the bonding interface. We systematically compare anti-phase with in-phase direct bonding, in which the lattice order is equivalent to that of hetero-epitaxially grown layers. Observation of structural properties confirmed successful elimination of threading dislocation in the layers of both types of direct bonding. Then the wafers were applied to the fabrication of InP-based long-wavelength lasers on GaAs substrates. We found that the level of laser performance was lower for the lasers fabricated by anti-phase direct bonding than those by in-phase direct bonding, however, such deterioration was only slight. Moreover, a very low degradation rate at 50°C has been continued for both kinds of lasers, which indicates good confinement of misfit dislocations at the bonding interface.

II. EXPERIMENTAL

Normal (001) GaAs and InP wafers were used in this study. All epitaxial growth was performed by conventional low pressure MOCVD. The direct bonding procedure was carried out as follows: The GaAs and InP wafers were placed face to face after chemical etching in a H_2SO_4+H_2O_2 solution and cleaning in dilute HF. Their crystallographic axes were adjusted by aligning their cleaved facets. They were loaded into the MOCVD reactor, and a pressure of 30 g/cm^2 was applied on them. Then they were heated to either 600°C or 700°C for 30 min in H_2. After heat treatment, the InP substrate was selectively etched by dilute HCl so as to leave the thin InP desired on the GaAs substrate.

III. STRUCTURAL PROPERTIES

Figure 1 shows the relation between the crystal axes of the GaAs and InP wafers with a schematic lattice structure. In type A, which corresponds to anti-phase direct bonding, the [110] orientations of the two wafers are aligned so as to be parallel. In this way, the lattice

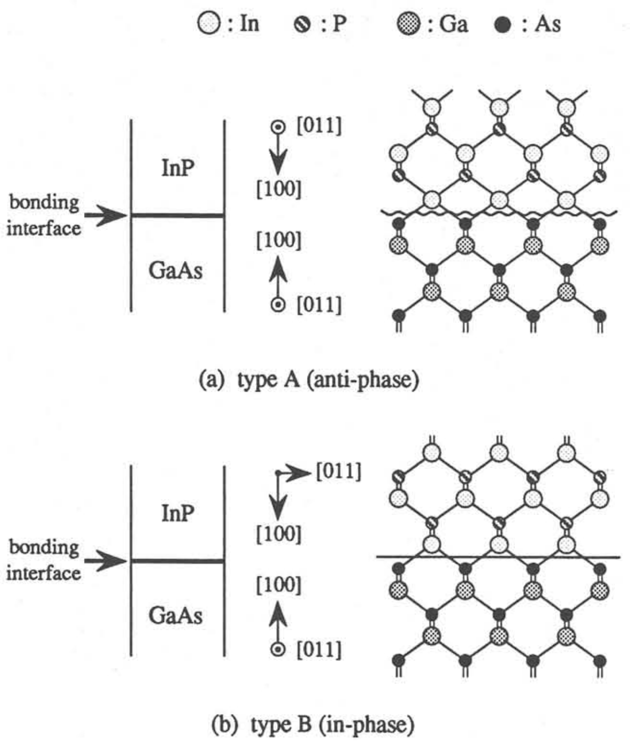

Figure 1 Relation of crystal axes between GaAs and InP wafers with schematic lattice structure: (a) type A, (b) type B. The wavy line in (a) shows the anti-phased boundary, whereas the straight line in (b) shows the in-phase boundary.

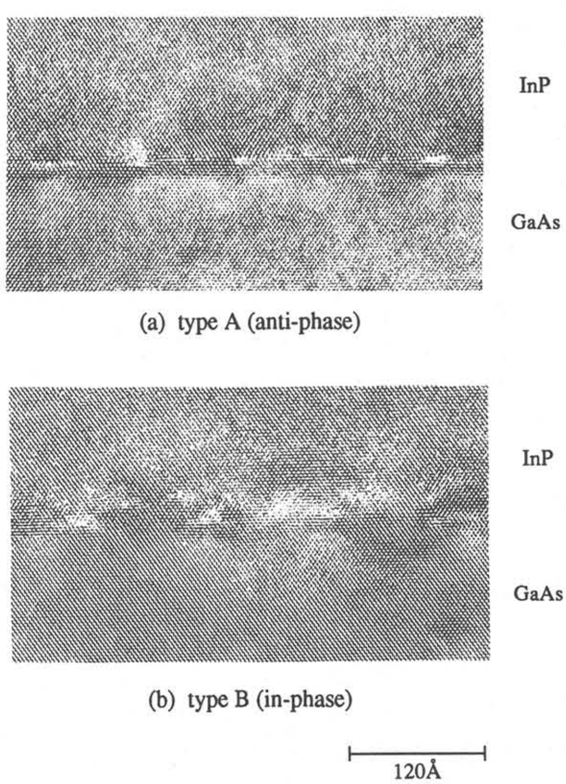

Figure 2 High-resolution cross-sectional TEM images around the InP/GaAs interface: (a) type A, (b) type B.

structure becomes symmetric at the bonding interface. Type B is in-phase direct bonding, in which the lattice order keeps the same zinc-blende structure consistently throughout both wafers. This is because the [110] orientation of the GaAs wafer is perpendicular to the [110] orientation of the InP wafer.

Although type A seems unlikely, the wafers were united with equivalent mechanical strength as in type B. Figure 2 shows cross-sectional images taken with a high-resolution transmission electron microscope (TEM) of the two samples. They were both heat treated at 600°C. In both types, misfit dislocations, most of which were the 90°-type, were observed at a constant spacing, as earlier researchers have reported[2,3]). The spacing was about 120 Å, which corresponds to a 3.6% lattice mismatch between InP and GaAs at 600°C. No threading dislocation was observed in low-magnification views, which indicates localization of misfit dislocations at the InP/GaAs interface. The crystal quality of the InP layers was evaluated by X-ray diffraction, and the FWHM of diffracted peaks was about 40 arcsec for both types. Therefore, it has been shown that the direct bonding of highly lattice mismatched wafers with such a peculiar interface is possible by realizing high-quality layers.

IV. APPLICATION TO LASER FABRICATION

We applied these two types of bonding to device fabrication. Figure 3 shows the schematic structure of an InP-based 1.55-µm unstrained MQW ridge-waveguide laser fabricated on a GaAs substrate. The layers for the laser was first grown upside down on a p-InP substrate, and then the wafer was directly bonded on two different n-GaAs substrates in the two ways described above (type A and B). Heat treatment was done at 700°C. After the InP substrate was selectively removed, a ridge-waveguide structure was formed by wet etching. The p-contact was formed on the InP layer and the n-contact on the back of the GaAs substrate.

Figure 4 shows the typical light-current and voltage-current characteristics of the lasers under CW operation at room-temperature. The cavity length is 300 µm and the cleaved facets are uncoated. Note that the threshold current does not differ between type A and B; however, slope efficiency is slightly lower for type A. In addition, type A shows higher turn-on

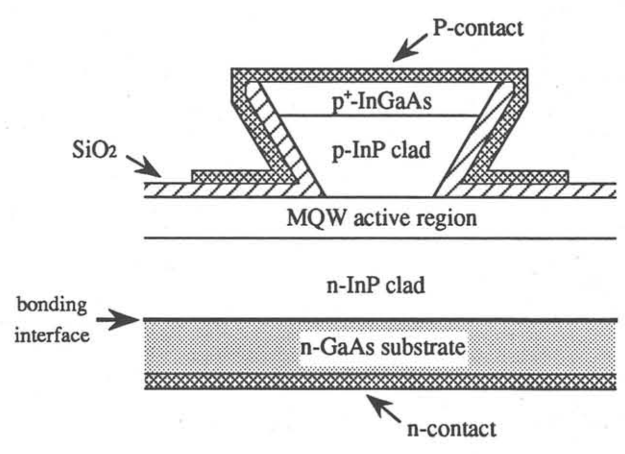

Figure 3 Schematic diagram of 1.55-µm MQW ridge waveguide lasers on GaAs.

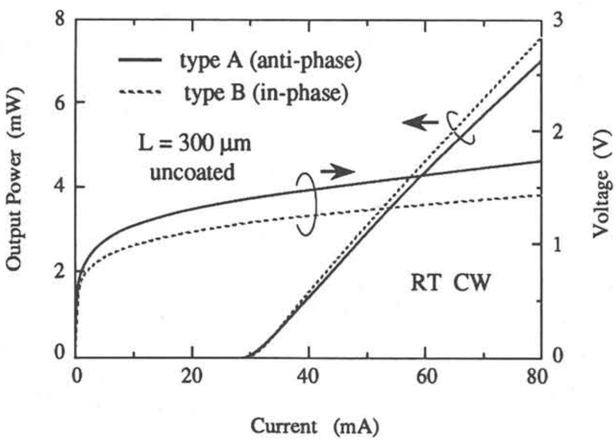

Figure 4 Light-current and voltage-current characteristics of the two types of lasers on GaAs.

voltage (V_F) and larger resistance (R). The larger R might be attributed to the increase in amorphous regions at the interface. The amorphous regions were actually observed by TEM for both types, in areas other than the continuously bonded areas shown in Fig. 2. Since the interface of type A is anomalous, there may be a greater tendency for the atoms to form amorphous regions in type A than type B. The higher V_F might be attributed to the same effect (increase in amorphous regions), or higher barrier heights at the abnormal interface. The lower slope efficiency might also be due to the influence of amorphous regions, but its origin is not clear. However, it should be noted that it is possible to fabricate devices with acceptable characteristics by anti-phase direct bonding.

Moreover, both types of devices showed high reliability. Figure 5 shows the results of a preliminary aging test conducted under CW operation at 50°C with a constant light output of 5 mW. The cavity length is 300 μm and the rear factes were coated with highly

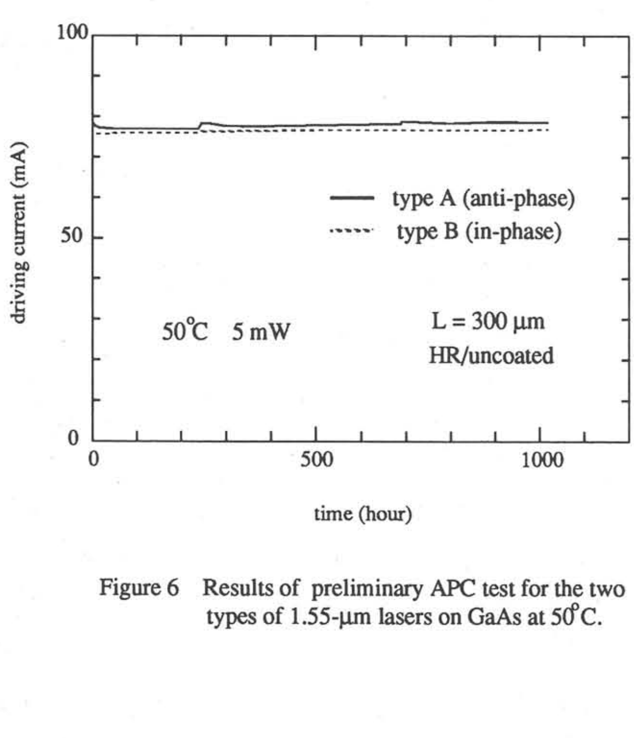

Figure 6 Results of preliminary APC test for the two types of 1.55-μm lasers on GaAs at 50°C.

reflective (HR) film. The increase in injected current is very low after 10^3 hours of operation, which suggests that the time needed to reach a 20% increase is about 10^5 hours. Such a small degradation rate is comparable to that of lasers homo-epitaxially grown on an InP substrate. This result indicates that the localized misfit dislocations at the bonding interface do not multiply or thread into the layers under current injection. We emphasize that this rigid localization was obtained for type A, as much as for type B. Therefore, direct bonding is indeed a superior technique for device fabrication involving unusual relations of crystallographic axes between the device and the substrate without degrading device performance, even if there is large lattice mismatch between them.

V. CONCLUSION

In summary, we investigated anti-phase direct bonding of InP and GaAs by comparing it with in-phase direct bonding. We found by TEM observation that anti-phase direct bonding was possible at the atomic level and that misfit dislocations were localized at the bonding interface. In device application, lower slope efficiency, larger resistance, and higher turn-on voltage were observed, which may be attributed to the increasing formation of amorphous regions, more so than in in-phase direct bonding, or higher barrier heights at the abnormal interface. Nevertheless, the lasers fabricated by anti-phase direct bonding still exhibit almost the same characteristics as those fabricated by in-phase direct bonding. Moreover, they showed high reliability which corresponds to a 20% increase in driving current after about 10^5 hours operation at 50°C and 5 mW. This means that rigid localization of misfit dislocations is obtainable not only by in-phase but also anti-phase direct bonding. Therefore, anti-phase direct bonding is a viable option for application to the monolithic integration of various devices.

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