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High-Speed GaAs Epitaxial Lift-Off and Bonding with High Alignment Accuracy Using a Sapphire Plate

Y. Sasaki,[a] T. Katayama,[a] T. Koishi,[a] K. Shibahara,[a] S. Yokoyama,[a,z] S. Miyazaki,[b] and M. Hirose[b]

[a]Research Center for Nanodevices and Systems, and [b]Department of Electrical Engineering, Hiroshima University, Higashi-Hiroshima 739-8527, Japan

We report more than one order of magnitude (~18 times) enhancement in the AlAs etching rate in a GaAs epitaxial lift-off technique compared with that at 0°C reported previously. This has been achieved by optimizing various physical parameters such as pressure and temperature, and by adding a surfactant and antifoaming agent to the HF solution. The sapphire plate on which the sample is adhered is useful in further processing. Thus, lifted-off GaAs/AlGaAs double heterostructures exhibit good luminescence characteristics compared to the as-grown samples.

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Recently, there has been an increasing interest in the research of optoelectronic integrated circuits (OEICs).[1-4] We reported previously on the fabrication of OEICs with optical waveguides, photodiodes, and complementary metal oxide semiconductor circuits on Si large scale integrated circuits (LSIs).[5] However, light-emitting devices have not been integrated into LSIs. The purpose of the study is to develop OEICs that incorporate light-emitting devices, and to demonstrate the advantages of the optical interconnection compared with metal interconnects. We have, so far, succeeded in fabricating and evaluating optical writing operations in a three-dimensional optically coupled common memory which consists of polished GaAs light-emitting diodes (LEDs) (120 μm thick) bonded on a Si memory LSI with indium micrometal bumps.[6] However, such thick LEDs are not suitable for multilayer three-dimensional integration. Thinner GaAs light-emitting devices are also favored for OEICs even though they are not three dimensional. Therefore, a new reliable technology for obtaining thinner GaAs devices is strongly required especially because the GaAs wafers are more fragile than Si wafers.

The epitaxial lift-off (ELO) technique,[7,8] in which an AlAs release layer (~10 nm) between the GaAs device structure and the GaAs substrate is selectively etched to remove the device layer, has been developed for mounting high-quality GaAs thin-layer devices onto Si LSIs. Compared with the ELO technique, the heteroepitaxial growth of III-V compound semiconductors still requires intense research effort to obtain high-quality devices. The etching selectivity of AlAs with respect to GaAs in diluted HF is reported to be $\sim 10^7$.[9] However, the etching rate of the AlAs release layer is still very slow (~0.1 mm/h) and impractical. The HF concentration of the etchant for the AlAs release layer was below 10 wt % and the etchant was cooled to 0°C in order to suppress the generation of H_2 gas bubbles (etching products). Bubble generation will disturb etchant inflow and product outflow through the narrow gap between the GaAs device layer and the substrate. We have already reported an eightfold increase (compared with that at 0°C) in the etching rate of the AlAs release layer by adding a surfactant and antifoaming agent to the etching solution and raising the etchant temperature to 40°C.[10] However, above 40°C, the etching rate decreases due to H_2 bubble generation.

In this paper, we report a further increase in the etching rate by a factor of ~18 by applying N_2 pressure of 5 kgf/cm^2 and raising the etchant temperature to ~50°C. The lifted-off film is then adhered onto a sapphire plate and transferred to a Pd-coated SiO_2/Si substrate[11] with high alignment accuracy using a three-dimensional wafer aligner.[12] Thus, lifted-off and bonded GaAs/AlGaAs double heterostructures on Si substrates exhibit good luminescence characteristics compared to the as-grown samples.

Experimental

A GaAs/AlGaAs double-hetero (DH) structure for ELO was grown on a GaAs substrate by molecular beam epitaxy with a 10 nm AlAs release layer. After coating the sample surface by Apiezon wax, the sample was cut and dipped in the following three solutions: (*i*) normal diluted HF (10 wt % HF in H_2O), (*ii*) diluted HF with a surfactant and antifoaming agent (10 wt %, S10, Morita Chemicals, Ltd.), and (*iii*) diluted HF with a surfactant and antifoaming agent under high pressure (5 kgf/cm^2) N_2 gas. The Apiezon wax coating induces strain in the sample and increases the gap between the GaAs device layer and the substrate. As a result, the etchant inflow and the removal of the etching products are enhanced. The temperature of the diluted HF solution was varied from 0 to 64°C. The lateral etching rate of the AlAs layer was determined from the time required to lift the GaAs device layer from the substrate. In order to check the separation of the GaAs device layer from the substrate, ultrasonic vibration was applied to the etching solution for 15 s every 30 min.

The sample handling problem, i.e., the difficult transfer of the thin, fragile GaAs film onto Si, is solved by using the special holder shown in Fig. 1. The GaAs film is transferred in the following sequence as shown in Fig. 2. Each LED is first isolated in the required size by mesa etching after formation of the ring electrode. Then the sample is adhered on a sapphire substrate with a resist. Sapphire is resistive to an HF solution. Instead of the warping induced by the Apiezon wax,[7] an artificial distortion is applied by a screw to enhance the etching. The sample remains on the sapphire plate after the lift-off process. Therefore, the alignment of the lifted-off sample to the bonding substrate becomes similar to a reticle alignment in the conventional stepper. The alignment is performed using a three-dimensional wafer aligner (Fig. 3). The sample is set on a vacuum chuck. An infrared light source installed below the wafer chuck is used for the alignment. The alignment accuracy is ±1 μm, which is limited by the wavelength of the infrared light. The lifted-off double-hetero LED was aligned and

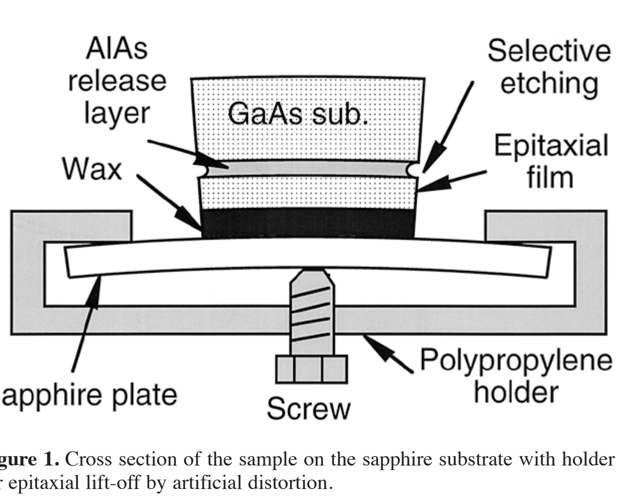

Figure 1. Cross section of the sample on the sapphire substrate with holder for epitaxial lift-off by artificial distortion.

[z] E-mail: yokoyama@sxsys.hiroshima-u.ac.jp

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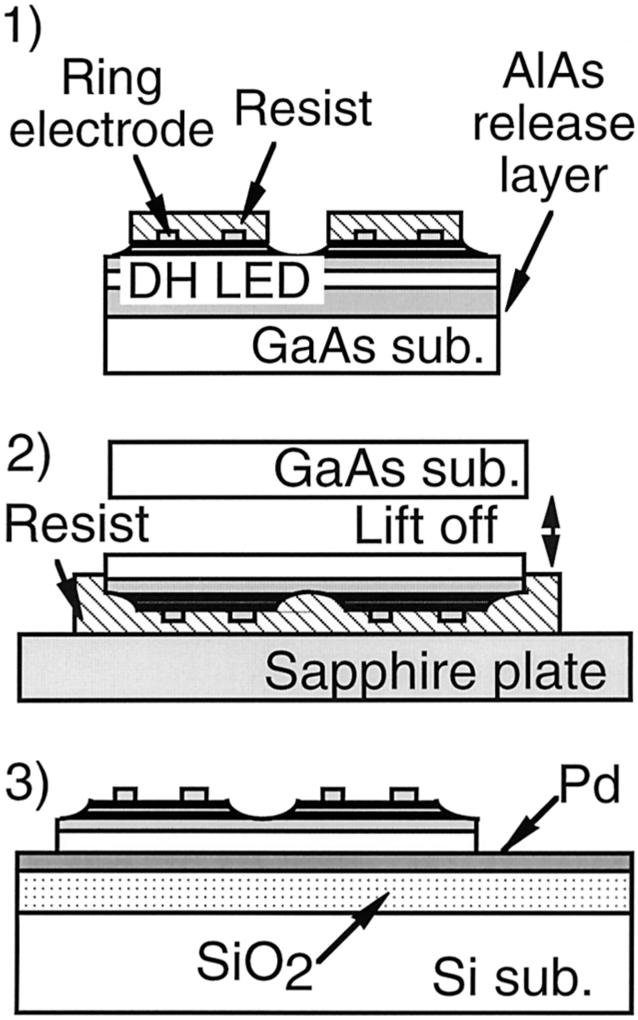

Figure 2. Bonding method of GaAs devices onto Si substrate: (1) Each LED is isolated by mesa etching after formation of the ring electrode. (2) The sample on a sapphire plate is lifted off by AlAs selective etching. (3) The sample is transferred onto a Pd/SiO_2/Si substrate using a three-dimensional wafer aligner. The GaAs and Pd are bonded by thermal annealing at 100°C for 60 min in air.

bonded onto a Pd coated SiO_2/Si substrate using deionized water[11] at ~100°C by means of this aligner. Finally, the sample was stripped off from the sapphire plate by dipping it in acetone.

Output light power and photoluminescence (PL) of the LED sample before and after the lift-off process were measured. The PL measurements were carried out with the pumping light of a semiconductor laser diode (785 nm in wavelength) at room temperature. The samples were mounted on a copper holder using an InGa alloy.

Results and Discussion

High-speed AlAs etching under high pressure conditions.—Under normal pressure conditions, the lateral etching rate of the AlAs layer (10 nm thick) is changed as a function of the temperature of the etching solution as shown in Fig. 4. Without a surfactant and antifoaming agent (open triangle) the etching rate decreases with increasing temperature. By increasing the temperature, the H_2 generation rate increases. On the contrary, the solubility of H_2 in the solution decreases with increasing temperature. Thus H_2 bubbles are generated upon increasing the temperature. The generated bubbles obstruct both inflow of the etchant and removal of the etching products through the narrow gap between the GaAs device layer and the substrate. As a result, the etching rate is decreased. By adding a surfactant and antifoaming agent (solid circle), the etching rate increases ~eight-fold compared with that at 0°C as the temperature reaches ~ 40°C. This is due to the effects of the surfactant and antifoaming agent, respectively, which enhance the diffusion of the etching product and suppress the generation of H_2 bubbles. Above 40°C, the etching rate decreases with increasing temperature due to two effects: (*i*) The hydrogen bubble generation rate exceeds the capacity of the antifoaming agent; (*ii*) The wax-induced strain might be reduced due to the softening of the wax, which results in the narrowing of the gap between the GaAs device layer and the substrate.

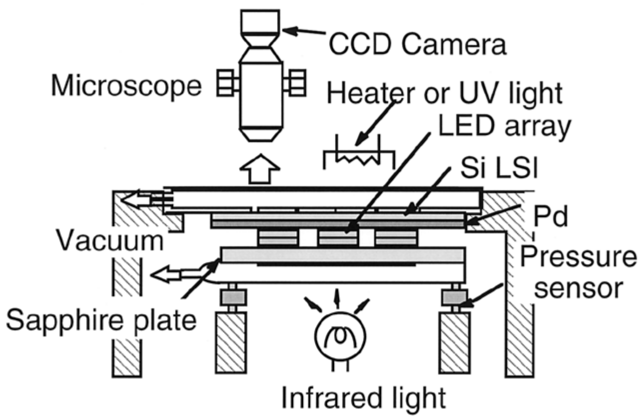

Figure 3. Mounting method of a LED on Si LSI using a three-dimensional wafer aligner.

By applying N_2 pressure (5 kgf/cm^2) in addition to the surfactant and antifoaming agent (open circle), the etching rate of the AlAs layer becomes faster than that at normal pressure, and increases ~18-fold as compared with that at 0°C, when the temperature reaches ~50°C. The effect of pressure is discussed here. The etching velocity of AlAs (v) is proportional to the molar concentrations of the dissolved H_2 (n).[7] According to Henry's law, n is proportional to the pressure, P. Then the simple equation

$$v = kP$$

where k denotes a proportionality factor, will be valid. From this equation, the etching rate is expected to increase in proportion to the pressure. Although the actual etching rate behavior is not simple as other factors such as sample warpage and chemical reactions are involved, the qualitative explanation of the enhancement of the etch rate due to the application of pressure seems feasible.

Light emission characteristics.—The input current/output light intensity characteristics of the DH LEDs before and after the lift-off

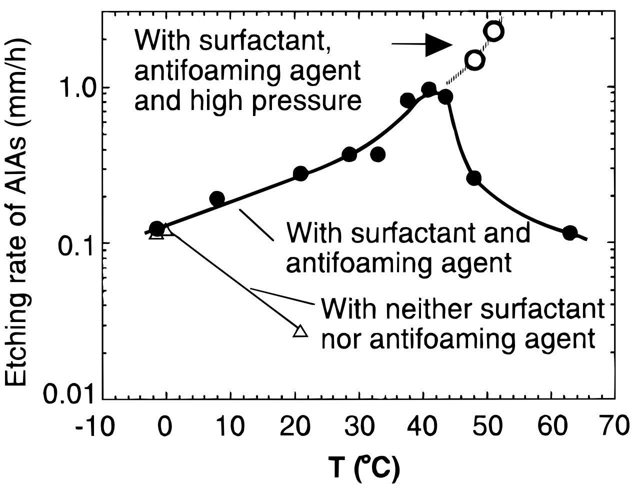

Figure 4. AlAs selective etching rate as a function of temperature of the HF solution.

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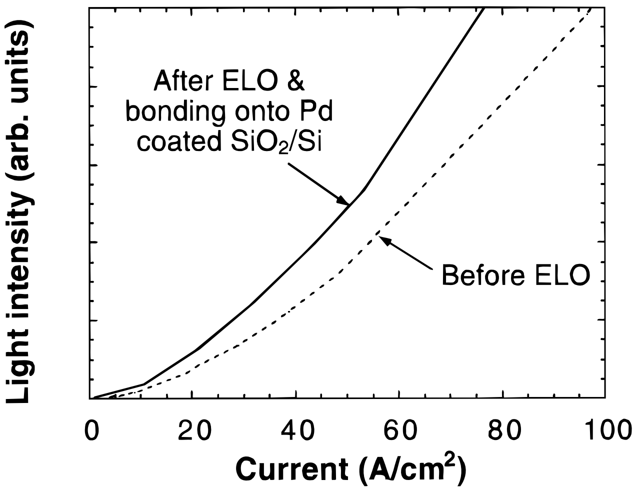

Figure 5. Light intensity vs. current for the LED before and after ELO.

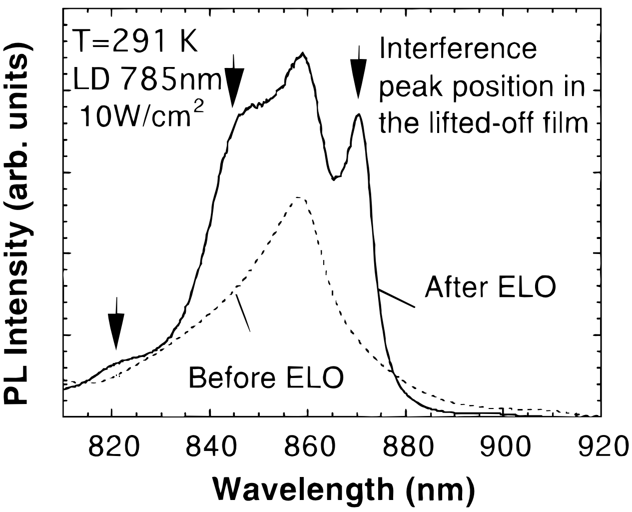

Figure 7. Photoluminescence spectrum before and after ELO.

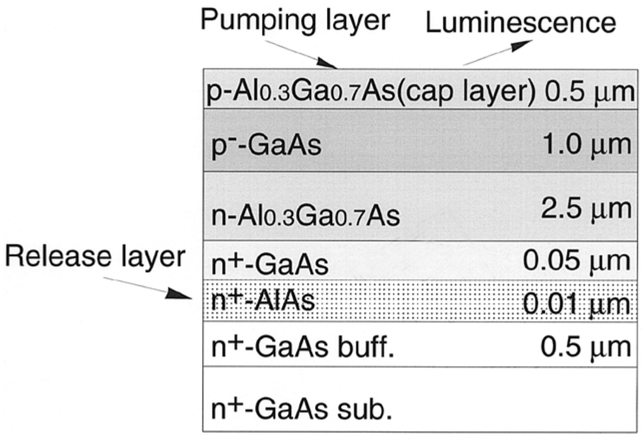

Figure 6. Sample structure for photoluminescence measurement.

process are shown in Fig. 5. It should be noted that the output light power of the lifted-off and bonded sample is more than that before the lift-off process. This is explained by the light reflection from the GaAs/Pd interface. This effect is preferable for the manufacture of OEICs. In order to obtain a higher light intensity, smaller light-emitting devices can be used.

For the PL measurement, we covered the sample with a $Al_{0.3}Ga_{0.7}As$ layer (Fig. 6) in order to reduce the influence of the high-density interface states at the GaAs/air interface. Figure 7 shows the PL spectra at room temperature for the DH structures before and after the lift-off process. The luminescence from these structures is detected by a charge coupled device camera in the wavelength range 810 to 920 nm. While the position of the main peak is not changed, three new peaks appear after the ELO process. These peaks might be due to an interference effect in the multilayer stacked structure of the lifted-off sample. The interference effect is only observed for the lifted-off sample because the light reflection at the back surface occurs only for the lifted-off sample. The integral intensity from 820 to 880 nm is increased 1.8-fold after the ELO process.

Conclusion

A high-rate (~18 times) epitaxial lift-off technique for GaAs devices has been achieved by adding a surfactant and antifoaming agent in diluted HF, raising the etchant temperature (~50°C) and applying high N_2 pressure (5 kgf/cm^2). We have developed an easy handling process for bonding lifted-off films onto Si substrates using a sapphire plate. The light intensity of the LED increases after the lift-off process. These results will contribute toward the fabrication of practical OEICs.

Acknowledgments

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