Room-Temperature Two-Color Lasing by Current Injection into a GaAs/AlGaAs Coupled Multilayer Cavity Fabricated by Wafer Bonding

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Abstract
Room-temperature two-color lasing was successfully demonstrated by current injection into a GaAs/AlGaAs coupled multilayer cavity for novel terahertz emitting devices. The structure was fabricated by direct bonding of (001) and (113)B epitaxial wafers, and two types of InGaAs multiple quantum wells were introduced only in the (001) side cavity. Lasing behavior was clearly observed for two cavity modes under pulsed current conditions at room temperature. We also found that intensity relation between two-color lasing can be tuned by pulse duration of the injection current.

1. Introduction
Terahertz (THz) wave sources based on semiconductor materials have been investigated because of the wide range of possible applications such as wireless communications, spectroscopy, and imaging. We have proposed compact and room-temperature operable THz emitting devices based on efficient difference-frequency generation (DFG) of two cavity modes realized in a GaAs/AlAs coupled multilayer cavity. The structure consists of two cavity layers and three distributed Bragg reflector (DBR) multilayers [1]. Note that the structure should be grown on a non-(001) substrate because DFG through the second-order nonlinear process is forbidden on a (001) substrate owing to crystal symmetry. Use of a (113)B substrate is beneficial because the epitaxial film shows the relatively large second-order nonlinearity as well as the good crystalline quality. In addition, DFG of the two modes was found to be strongly enhanced by eliminating cancellation effect of the nonlinear polarizations realized in two cavity layer regions. This can be accomplished by face-to-face bonding of two halves of the coupled cavity structure grown on different substrate wafers [2]. From the viewpoint of device applications, the two modes should be generated inside the coupled cavity structure, which would enable THz emission without external light sources.

Recently, we fabricated the wafer-bonded GaAs/AlGaAs coupled cavity that had InGaAs multiple quantum wells (MQWs) in one of the cavity layers [3]. The threshold behavior was clearly observed in the current-light output (I-L) curve of the surface-emitting device based on the coupled cavity. However, two-color lasing was not realized at room temperature because of the wavelength mismatch between the cavity modes and gain peaks of the MQWs. In this study, we successfully demonstrated room-temperature two-color lasing by using the finely tuned coupled cavity. The lasing properties were measured under pulsed conditions and its dependence on the pulse duration was also studied.

2. Device structure
The single cavity structures were individually grown on a (113)B- and (001)-oriented GaAs substrates by molecular beam epitaxy (MBE). The (113)B side cavity consists only of a GaAs layer with an optical thickness of 3λ/2, while three-period InGaAs/GaAs MQWs with two different well widths were introduced in the 3λ/2-thick GaAs cavity of the (001) side. The thickness of each layer was carefully set to a specific value so that two-color lasing was enabled at room temperature. The two epitaxial wafers were directly bonded by the surface activated bonding method at room temperature. After the bonding, the (001) GaAs substrate was completely removed by mechanical polishing and selective wet etching. Using the coupled cavity structure prepared as mentioned above, we fabricated the current-injection surface-emitting devices (Fig. 1) by the following procedure. First, circular mesas with diameters of 80-100 µm were formed by wet chemical etching. A 44.1-nm-thick AlAs layer inserted just above the (001) side cavity was selectively oxidized for current confinement. Then, n-type metal electrodes (AuGe/Ni/Au) were deposited on the surface of the n-type DBR. The mesas were buried in polyimide. Finally, p-type electrodes (Ti/Au) with the optical windows were deposited on the surface of the p-type DBR, followed by rapid thermal annealing in nitrogen atmosphere.

![Fig 1. Schematic view of the surface-emitting device.](image-url)
3. Lasing properties

Optical emission properties of the devices were studied at room temperature using a pulsed-current source with a repetition rate of 1 kHz. The pulse duration was varied from 0.5 to 5 µs. Figure 2 shows a picture of the fabricated device under pulsed operation at an injection current of 60 mA with a pulse duration of 0.5 µs. The I-L curve of each device was measured using an InGaAs p-i-n photodiode. The emission spectra at various operation conditions were also measured using a spectrometer equipped with a thermoelectrically cooled Si charge-coupled device array.

Figure 3 shows the I-L curves measured with various pulse durations. The threshold behaviors were clearly observed in all the I-L curves and the threshold current of ~50 mA was almost the same with each other. However, the decrease of the light output in the high-injection current region was significant for a long pulse duration of 5 µs because of heat generation in the device.

Figure 4 plots the pulse duration dependence of the emission spectrum measured at the injection current of 90 mA, which was above the threshold current of the device. Two sharp peaks at 917.3 and 924.8 nm were clearly observed in all the spectra, indicating that room-temperature two-color lasing of the device was successfully realized for each case. The optical frequency difference of two peaks was 2.65 THz. Note that the intensity relation between two-color lasing in the device was clearly dependent on the pulse duration. Emission intensity of the long-wavelength mode relative to the short-wavelength mode increased with increasing pulse duration. This might be due to the slight redshift of the MQW gain peaks caused by the weak heat generation depending on the pulse duration. This feature is useful for THz generation since the DFG is efficient when two-color lasing is enabled with identical intensities.

4. Conclusions

Room-temperature two-color lasing was successfully demonstrated by current injection into the wafer-bonded GaAs/AlGaAs coupled multilayer cavity. The structure was fabricated by direct bonding of the (001) and (113)B epitaxial wafers grown by MBE. InGaAs MQWs with two different well widths were introduced only in the (001) side cavity. The current-injection surface-emitting devices were fabricated using the wafer-bonded coupled cavity. The threshold behavior was clearly observed in the I-L curve measured at room temperature under pulsed conditions and two lasing peaks with frequency difference of 2.65 THz were observed in the spectrum measured at the injection current above the threshold. We also found that intensity relation between two-color lasing can be tuned by the pulse duration.

References