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True near-field optical characters of a GaAlAs semiconductor laser diode

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In this research we have taken advantage of near-field scanning optical microscopy, a recently developed technique, to test the optical nature of GaAlAs semiconductor laser diodes working at 780 nm. With this method, both the images of the topographic and the near-field intensity of the laser diodes can be simultaneously obtained. With the obtained results, we can analyze the variety of the geometric structure, the local near-field optical intensity, the propagating modes, and the near-field mode-field diameter at different working states of the laser diodes. Hereby, we can find the factors that affected the radiation cavity of the laser diode and explore its alive state. © *1999 American Institute of Physics.* [S0034-6748(99)01112-0]

I. INTRODUCTION

The laser diode is one of the powerful components in industrial and academic circles; it is, therefore, important to further investigate its irradiant efficiency by studying the relation between the topography and the optics nature in the active region. Currently, the combination of transmission electron microscopy (TEM) (Refs. 1 and 2) and charge-coupled device imaging systems is employed to test the roughness and the near-field pattern (NFP) of laser diodes. However, the high-energy bombardment of the electron beam in TEM must be performed in vacuum and this process may easily destroy the sample surface. In addition, the optical resolution of the NFP is diffraction limited and impossible to compare with the TEM image.

In this article, we report a simple and rapid method to solve the problem of using TEM imaging. We use a tapping-mode near-field scanning optical microscopy (NSOM) system to test the optical characteristics of multiple-quantum-well (MQW) semiconductor laser diodes. Basically, the NSOM system consists of the technique of scanning probe microscopy and the application of a nanoscale optical fiber probe. The bent fiber probe[3–5] works as a detector for making three-dimensional near-field scanning in the operation of a tapping-mode atomic force microscope (AFM). Information is collected at the tip of the fiber probe and both the images of the near-field intensity profiles of the propagating modes and the topographic features of the illuminated region can be accomplished. Various working states of the laser diode, including natural attenuation and factitious destruction, have been successfully studied by this novel method.

II. EXPERIMENT

The geometric structure of the 780 nm semiconductor laser diode consists of an *n*-doped and a *p*-doped AlGaAs layer, a GaAs layer, and the active MQW layers.[6,7] The active region of the MQW layers, sitting between the *p*-type and *n*-type layer, is the area of great irradiation. This active region is the main topic in this experiment.

We made use of the atomic force microscope (Multi-Mode Nanoscope III, Digital Instruments) with some modifications and utilized a fiber as a tip to detect the optical signal. The setup diagram was shown in Fig. 1. The fiber probe diameter at the tip was around 50–100 nm. It was fabricated by the fiber puller (Sutter P-2000) and further coated with a Pt/Pd layer using an ion sputtering method to form the surface with a thickness of around 30–40 nm so that a nanometer-scale optical aperture at the tip of the probe could be achieved. From foregone experience,[8,9] it is realized that the Al-coated fiber tip is easily destroyed by local heating from the light-emitting sample. We avoided this by using the Pt/Pd-coated fiber tip, as the melting point of the Pt/Pd (around 1770 °C), is higher than Al (around 660 °C). In this way, the accuracy of the near-field optical signal is improved significantly. The Q factor and resonant frequency of the bent fiber probe were 200 and 350 kHz, respectively. The laser diode, mounted on a *xyz* piezotranslator, was excited by the current source and modulated at 83 kHz using a function generator. The near-field optical signal retrieved by the bent fiber probe was further amplified by a photomultiplier (R928, Hamamatsu) and fed through a lock-in amplifier (SR830, Standford Research Systems) before being further processed by a computer. In this way, both the surface topography and near-field optical images of the laser diodes could be obtained simultaneously.

III. RESULTS AND ANALYSIS

A 5 mW GaAs/AlGaAs diode emitting at 780 nm (RLD-78 MA) was used in this study. The output power of

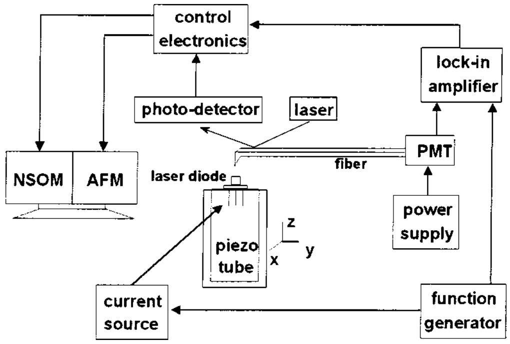

FIG. 1. Collection-mode imaging of the laser diode by NSOM.

the laser diode, known as the far-field total emitted intensity, illuminated as a function of the injection current, is shown in Fig. 2. It was measured by a power meter sitting 1 mm above the illuminated end of the laser diode. Generally, the output power increased tremendously once the injection current excited beyond the lasing threshold (35 mA) [Fig. 2, curve (a)]. It was observed that: (i) The laser diode with its shell removed and exposed in air for several days, would have its lasing efficiency attenuated by approximately 35% once the injection current crossed the threshold limit, as indicated in Fig. 2, curve (b). (ii) When the laser diode operated above the maximum allowable value (60 mA), its surface would be severely affected, resulting in a low output power, as shown in Fig. 2, curve (c). These two different kinds of working states of laser diodes in the NSOM system are further elaborated as follows.

A. Natural attenuation

The AFM and NSOM images of the laser diode presented in Figs. 3(a) and 3(b) correspond to the conditions in Fig. 2, curves (a) and (b), measured at an injection current of 45 mA. The geometry of the laser heterostructure was well

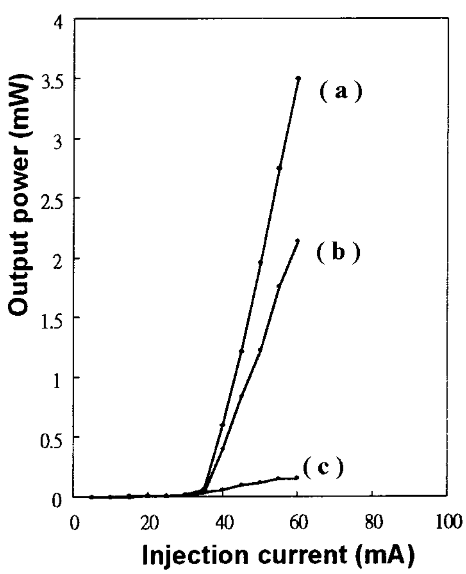

FIG. 2. Output power as a function of injection current of the cap-removed laser diode: (a) in the normal lasing state; (b) after being exposed to air for several days; and (c) after the laser diode is burned beyond its maximum allowed current.

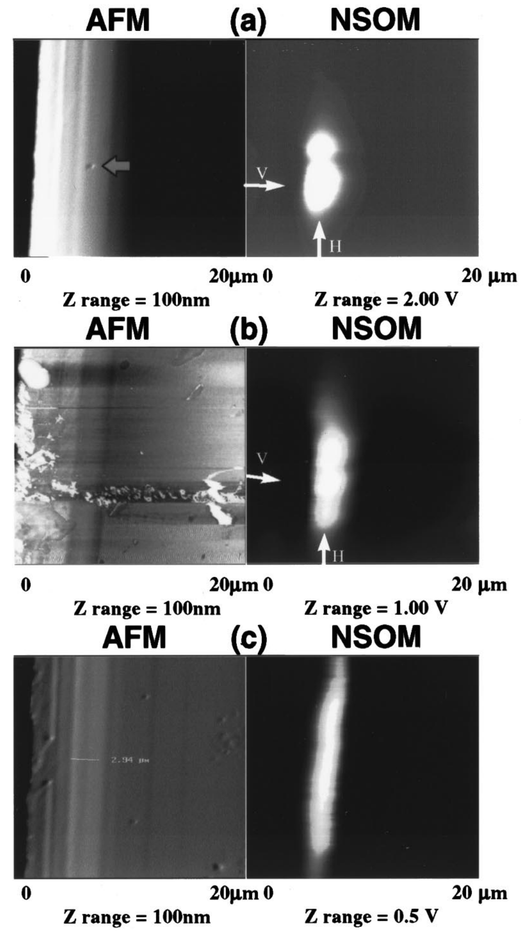

FIG. 3. AFM and NSOM images (size 20 μm$\times$20 μm) of a 780 nm MQW GaAs/GaAlAs laser diode measured at an injection current of 45 mA. These images of (a), (b), and (c) correspond to curves (a), (b), and (c), respectively, as stated in Fig. 2.

resolved in the AFM images. Analysis of the horizontal (H direction) and vertical (V direction) cross-sectional intensity profiles of the NSOM images of Figs. 3(a) and 3(b) are displayed in the upper and lower sides of Figs. 4(a) and 4(b), respectively. The peak value of the intensity profile coincided with most of the active region in the laser diode. A defect was found in the roughness of the active region, indicated by an arrow sign in the AFM image of Fig. 3(a). This defect caused the near-field transverse mode (TE_{00}) to separate into two modes [refer to the upper side of Fig. 4(a)]. By using the NSOM system to test the same laser diode after leaving it in air for several days, we could clearly observe some particles, inferred to be Al oxide, on the illuminated end from the AFM image in Fig. 3(b). The laser diode was working as curve (b)'s state, as shown in Fig. 2. From the upper side of Fig. 4(b), it could be easily noticed that the near-field pattern along the H direction occurred at the high-order transverse mode (TE_{01}) and its maximum local near-field optical intensity had been approximately reduced to 25% in comparison to the upper side of Fig. 4(a). Inspecting the lower sides of Figs. 4(a) and 4(b), the near-field mode-field diameter (MFD) along the *V* direction had been raised substantially from 2.019 to 4.395 μm. These phenomena, the diffusion and decay of the near-field propagation modes and

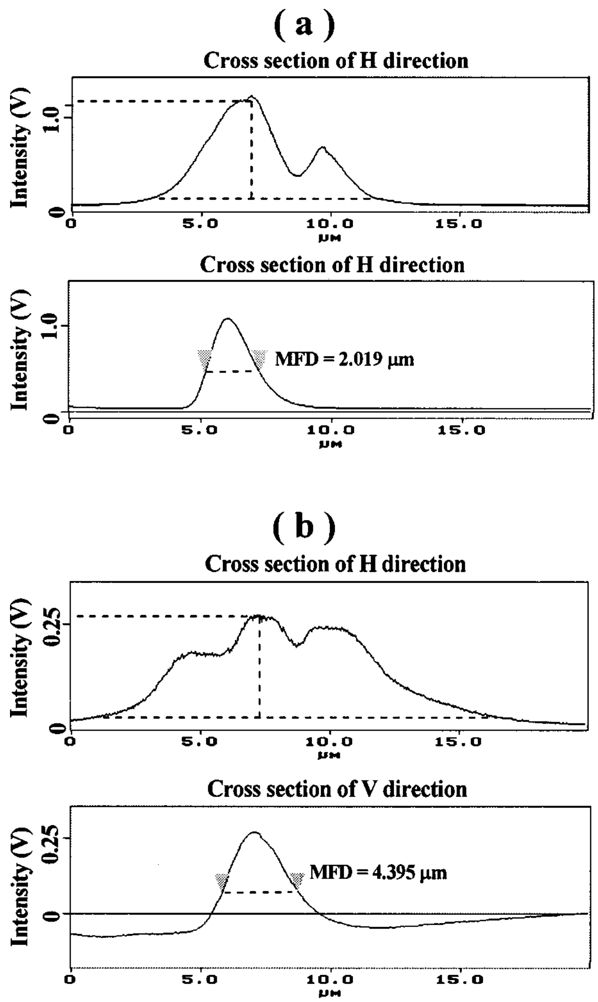

FIG. 4. Cross-sectional intensity profiles corresponding to the conditions in Figs. 3(a) and 3(b): (a) the horizontal and vertical intensity profiles in the normal lasing state and (b) the horizontal and vertical intensity profiles after being exposed to air for several days.

intensity, depended on the change of Al-doped concentration in the laser diode caused by oxidation, which was previously fixed during expatiating growth. Therefore, mass-produced semiconductor laser diodes normally fill with some gas in the shell, like nitrogen, to decrease the efficiency of the semiconductor's oxidation and extend its lasing lifetime.

B. Factitious destruction

The AFM and NSOM images in Fig. 3(c) correspond to the conditions in curve (c) of Fig. 2 measured at an injection current of 45 mA. The layers' structure was broken purposely by applying a current (70 mA) beyond the maximum allowable value (60 mA). A gap was also displayed in the AFM image of Fig. 3(c). The NSOM image of Fig. 3(c) indicated further elongation of the active region in the horizontal direction and its maximum local near-field optical intensity had fallen to 0.13 V. In this state, stimulated emission could no longer be sustained since the electrons were unable to be collected effectively. The irradiative condition was similar to that of a light-emitting diode.

IV. DISCUSSION

In summary, we have employed AFM and NSOM imaging to investigate laser diodes in various conditions. In addition to improving the spatial resolution, the above techniques also have the following advantages:

(i) They are nondestructive, unlike in scanning electron microscope imaging, where the sample surface always remains intact, consequently causing damage on the sample surface.

(ii) The observation can be performed during expatiating growth directly without any complicated sample preparation and stringent working environment.

(iii) They are complementary. Near-field imaging can supplement the measurement of the far-field emissive pattern.

Further investigation with microspectroscopy[10] will be performed in the near future to improve the laser-beam quality of the laser diode.

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