An application of the apertureless scanning near-field optical microscopy: Imaging a GaAlAs laser diode in operation

R. Bachelot,[a] G. Wurtz,[b] and P. Royer[c]
Laboratoire de Nanotechnologie et d'Instrumentation Optique, Université de Technologie de Troyes, 12 rue Marie Curie-BP 2060-10010 Troyes Cedex, France

(Received 31 July 1998; accepted for publication 5 October 1998)

The imaging of a commercial GaAlAs semiconductor laser emitting at 0.78 μm has been performed by apertureless scanning near-field optical microscopy using a sharp metallic tip. This tip was used as an optical and force probe simultaneously. In stimulated emission, we observed the single transverse laser mode whose dimensions are in good agreement with theoretical results. In spontaneous emission, an optical contrast linked to the known laser layers structure was observed.
© *1998 American Institute of Physics.* [S0003-6951(98)02349-3]

The spatial dimensions of the active region of the semiconductor lasers are generally in the micronic range. Consequently, the spatial distribution of the light generated by the laser active layer cannot be characterized with precision by the conventional optical microscopy whose resolution is limited by the diffraction to about 1 μm. Nevertheless, the submicronic characterization of these optoelectronic components would have several interests, for example to detect the local defects in the emitting area (due to, e.g., carriers leakage or epitaxial growth inhomogeneties) or to directly read and control the transverse modes of the optical cavity. This local study has recently been made possible by aperture scanning near-field optical microscopy (SNOM).[1–3] In this technique, a submicronic diameter aperture in a metallic screen (these probes are metallized tapered optical fibers) picks up the optical near field,[4] permitting the direct reading of the emission profile of the laser diode at the crystal surface.

The purpose of this letter is to show that this study is also possible by using the second family of SNOM, namely the ''apertureless SNOM.'' [4–8] This technique uses a homogeneous sharp tip whose extremity acts as a Rayleigh particle by scattering the optical near field of the sample to convert it into propagating waves which are far-field detected. By using such sharp apertureless tips, in addition to the advantages described in Ref. 6 (including the easiness of probe manufacture), we hope to minimize two dramatic problems which can arise when studying a laser diode in operation with an aperture metallized probe: heating of the fiber-tip leading to thermal expansion and damage of the tip,[3] and perturbation of the stimulated emission process due to multiple reflection between the laser and the metallic screen surrounding the optical aperture. Furthermore, this work should contribute to a best comprehension of the apertureless SNOM, particularly the role of the experimental parameters specific to this microscopy.

Figure 1 represents schematically the studied sample. It is a commercial laser diode [SHARP LT020MC, V-grooved substrate internal stripe (VSIS) structure, threshold current $=41$ mA, $\lambda=780$ nm, maximum optical power$=3$ mW] whose protection window has been removed. It is made of a double heterojunction ($Ga_{1-x}Al_xAs/GaAs/Ga_{1-x}Al_xAs$)[9–11] whose emission area is represented in gray in Fig. 1. The centered active layer uses a V-shape *p*-type cladding layer to effectively move the emission point closer to the chip center by confining, parallel to the junctions, the injection current (and thus the laser oscillation) to a narrow strip. Perpendicular to the junctions, the light is confined by both the energy bands structure (the double heterostructure confines the injected carriers to the 200-nm-thick active layer) and the high refractive index of the active layer which constitutes an optical waveguide with the two Al-doped cladding layers. In this way, in the case of stimulated emission, the laser generates a single transverse mode whose far-field intensity pattern is pseudo-Gaussian, analogously to the fundamental transverse mode of many gas lasers, but elliptic in shape. The polarization state of the emitted light is elliptic with the electric vector mainly parallel to the junctions (to the *X* axis in Fig. 1).

Our apertureless SNOM, whose detailed description is given in Ref. 12, has been developed, in a clean room, from a commercial scanning probe microscope (model M5 from

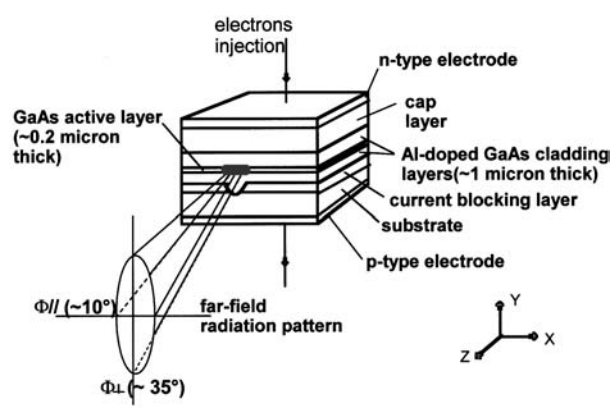

FIG. 1. Structure of the laser diode studied in the near-field zone (see text for precise description). The *Y* axis is parallel to the growth direction. During near-field imaging, the axis of the probe tip is parallel to the *Z* axis and the scan is in the (*X*,*Y*) plane.

[a]Electronic mail: renaud.bachelot@univ-troyes.fr
[b]Electronic mail: gregory.wurtz@univ-troyes.fr
[c]Electronic mail: pascal.royer@univ-troyes.fr

 © 1998 American Institute of Physics
Downloaded 25 Mar 2002 to 146.137.40.76. Redistribution subject to AIP license or copyright, see http://ojps.aip.org/aplo/aplcr.jsp

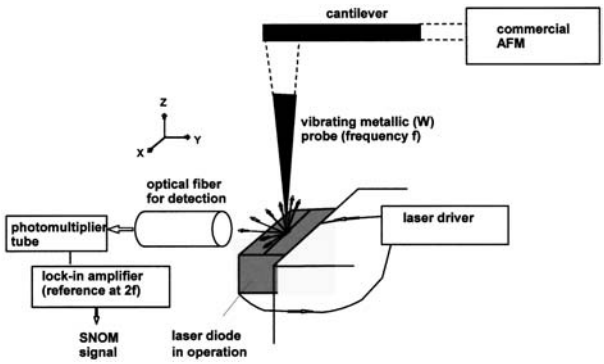

FIG. 2. Experimental SNOM configuration used for studying the laser described in Fig. 1.

Park Scientific Instruments). The experimental configuration used here is shown in Fig. 2. The optical probe is a sharp tungsten tip similar to that used in Refs. 6 and 8. The tip size is controlled by scanning electronic microscopy. Its terminal radius is less than 50 nm. It vibrates (at the f frequency) perpendicularly to the sample and scans in near-field zone the light-emitting active region, while the tip-to-surface distance is controlled by an atomic force regulation in the intermittent-contact mode (also called ''tapping mode''). Simultaneously to this atomic force microscopy (AFM) function, the optical scattered flux, from the tip end in local interaction with the sample, is far-field collected by a photomultiplier via an optical fiber (100 μm core/140 μm cladding, numerical aperture$=0.48$, probe-to-fiber distance $\sim$100 μm). A lock-in detection provides the SNOM signal. Preliminary experiments have permitted us to define a set of experimental parameters suitable for this study: probe vibration amplitude $\sim$100 nm, detection fiber at grazing direction and perpendicular to the laser junctions, SNOM lock-in detection at the frequency $2f$. These parameters values, as well as the tapered tip shape, minimize the contribution of the light scattered by parts of the probe other than its extremity (i.e., tip body+cantilever). Presently, we are working on the physical significance of these parameters.

Figure 3(a) shows the intensity pattern obtained in stimulated emission (injection current$=45.5$ mA). It displays a unique intensity pattern resembling the single mode expected. Figure 3 is in good agreement with both theoretical results and the specifications given by the manufacturer. Indeed, the cross section in the Y direction [Fig. 3(b)] reveals a width, measured at $I_{\max}/e^2$, of 1.5 μm ($=d_y$). In Ref. 9, this double heterojunction with a 200-nm-thick Al active layer is theoretically studied and described in details. Comparing Fig. 3(b) and the theoretical results of Ref. 9, the transverse confinement factor Γ_Y (related to the transversal expansion of the mode perpendicular to the junctions, beyond the active layer) is found equal to 0.4. This value of Γ_Y, depending on the Al molar fraction (x), leads to the following composition of the cladding layers: $Ga_{0.85}Al_{0.15}As$. It has been shown[9] that x must be below 0.37 so that the $Ga_{1-x}Al_xAs$ alloy keeps a direct band gap, making the stimulated emission process always possible. A cross section (not represented here) in the X direction reveals a width d_x, at $I_{\max}/e^2$, of 3.7 μm. This X confinement is ensured by the VSIS structure. Usually, one evaluates the size (d_x,d_y) of the emitted mode in

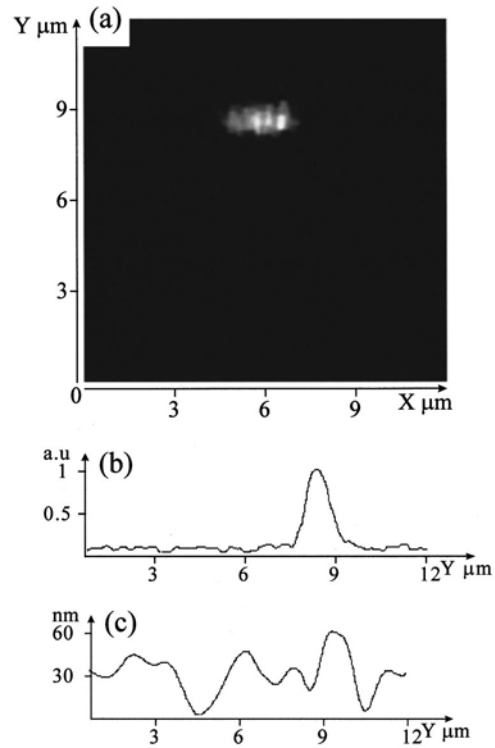

FIG. 3. Stimulated emission from the laser diode (injection current $=45.5$ mA). (a) 12 μm$\times$12 μm SNOM image showing the laser single mode. (b) SNOM profile along $X=6$ μm. (c) Simultaneously obtained corresponding AFM profile.

near field by numerical methods based on an inverse Fourier transform of the far-field intensity distribution.[11] The measurement of angles $\phi_\parallel$ and $\phi_\perp$ leads to the knowledge of (d_x,d_y), by the expressions: $d_x=\lambda/\phi_\parallel$, $d_y=\lambda/\phi_\perp$. In our case, using the experimental values of d_x and d_y, we calculated the far-field diffraction angles: $\phi_\perp=30°$ and $\phi_\parallel=12°$. These values are in good agreement with the values given by the manufacturer, i.e., $35°\times 11°$. Figure 3(c) shows the AFM profile corresponding to Fig. 3(b). It does not correlate with the SNOM profile and presents some fluctuations (of about 40 nm) which are not observed when the laser is off. Complementary experiments are in progress to interpret these fluctuations. Presently, we do not think that they correspond to thermal expansion of probe or sample, for two reasons: the fluctuations appear even if the tip scans at a few microns distance from the sample surface (not in contact), and in Fig. 3(c) they are not localized at the laser active region. They should be rather due to thermal effects perturbing the cantilever oscillation. Indeed, during scanning, both tip and cantilever are illuminated by the diverging beam issued from the active region. This can lead to heating of parts of the W wire. Considering the thermal conductivity of the tungsten ($=173$ W m^{-1} K^{-1}), the temperature increase could be transmitted to the whole W wire. Then, this would affect the W Young modulus and thus also the cantilever stiffness constant and resonance frequency. It should be noted, however, that despite this effect the vibration amplitude was kept constant during scanning by the AFM feedback loop.

Figure 4(a) shows the intensity pattern measured in spontaneous emission (injection current$=20$ mA). In this case, the single mode pattern has vanished and an optical

Downloaded 25 Mar 2002 to 146.137.40.76. Redistribution subject to AIP license or copyright, see http://ojps.aip.org/aplo/aplcr.jsp

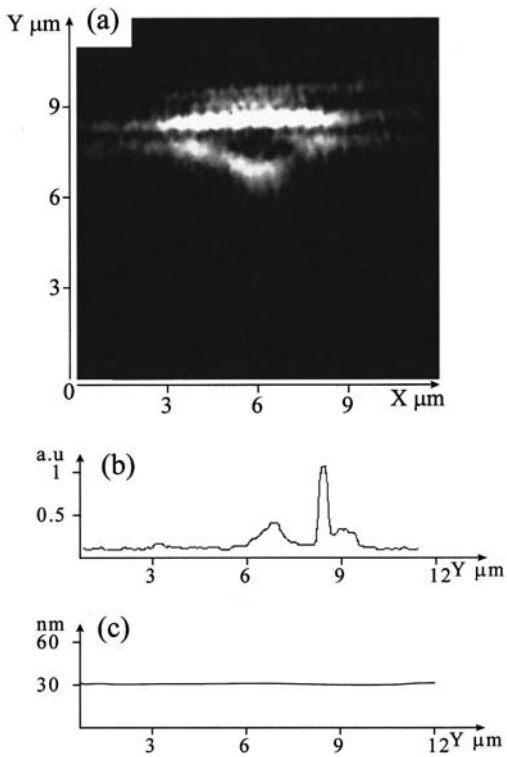

FIG. 4. Spontaneous emission from the laser diode (injection current $=20$ mA). (a) 12 μm$\times$12 μm SNOM image showing an optical contrast linked to the refractive index contrast of the laser front facet. (b) SNOM profile along $X=6$ μm. (c) Simultaneously obtained corresponding AFM profile.

contrast can be observed not only in the expected emitting zone but also in adjacent regions. Several stripes are clearly visible. The respective shapes of these bands correspond to these of the layers which form the double heterojunction (see Fig. 1). Especially, we discern three parallel bands. One of them presents a V shape comparable to that of the *p*-type cladding layer (VSIS structure in Fig. 1). The two other stripes would thus correspond to the active layer and the *n*-type cladding layer. Therefore, in the case of the spontaneous emission, a sample surface zone larger than the expected emitting one seems to be illuminated by the source. We interpret this behavior by the fact that, in the semiconductor crystal, the spontaneous process gives rise to photons emitted into a large angle. Most of these photons do not satisfy the conditions of optical guiding in the active layer. A photon leakage occurs then in the surrounding layers which are consequently also illuminated. Thus, in this case our SNOM experiment seems able to describe an optical contrast linked to the refractive index contrast of the sample surface. The cross section along the Y axis [Fig. 4(b)] reveals the high resolution with which the various layers of the laser are described. In particular, we can note, at $Y\sim 9.5$ μm, the abrupt increase of the SNOM signal when scanning from the cap layer to the *n*-type cladding layer, revealing a resolution of $\sim$100 nm. The brightest stripe, at $Y\sim 8.4$ μm, corresponds to the 200-nm-thick active layer. Its apparent width of 350 nm is due to both the resolution and the extension of the mode partially established in the laser cavity. According to Fig. 4(b), it is possible that the V-shape *p*-type cladding layer (from $Y\sim 6$ μm to $Y\sim 8$ μm) presents index gradients. Figure 4(c) shows the AFM profile corresponding to Fig. 4(b). It does not correlate with the SNOM profile and presents some fluctuations (of about 3 nm) which are negligible compared to Fig. 3(c).

It should be pointed out that neither the laser diode nor the probe tip was damaged by these experiments.

In conclusion, it has been shown that the apertureless SNOM can permit the near-field study of laser diodes in operation. The results presented both here and in Ref. 8 show that the apertureless SNOM using a sharp metallic tip is a powerful tool for local characterization of components in microelectronics and optoelectronics.

[1] S. K. Buratto, J. W. P. Hsu, J. K. Trautman, E. Betzig, R. B. Bylsma, C. C. Bahr, and M. J. Cardillo, J. Appl. Phys. **76**, 7720 (1994).
[2] U. Ben-Ami, N. Tessler, N. Ben-Ami, R. Nagar, G. Fish, K. Lieberman, G. Eisenstein, A. Lewis, J. M. Nielsen, and A. Moeller-Larsen, Appl. Phys. Lett. **68**, 2337 (1996).
[3] Ch. Lienau, A. Richter, and T. Elsaesser, Appl. Phys. Lett. **69**, 325 (1996).
[4] M. A. Paesler and P. J. Moyer, *Near-field Optics* (Wiley, New York, 1996).
[5] Y. Inouye and S. Kawata, Opt. Lett. **19**, 159 (1994).
[6] R. Bachelot, P. Gleyzes, and A. C. Boccara, Appl. Opt. **36**, 2160 (1997).
[7] F. Zenhausern, Y. Martin, and H. K. Wickramasinghe, Science **269**, 1083 (1995).
[8] A. Lahrech, R. Bachelot, P. Gleyzes, and A. C. Boccara, Appl. Phys. Lett. **71**, 575 (1997).
[9] H. C. Casey and M. B. Panish, *Heterostructure Lasers* (Academic, New York, 1978).
[10] S. L. Chuang, *Physics of Optoelectronic Devices* (Wiley, New York, 1995).
[11] E. Rosencher and B. Vinter, *Optoélectronique* (Masson, Paris, 1998).
[12] G. Wurtz, R. Bachelot, and P. Royer, Rev. Sci. Instrum. **69**, 1735 (1998).

Downloaded 25 Mar 2002 to 146.137.40.76. Redistribution subject to AIP license or copyright, see http://ojps.aip.org/aplo/aplcr.jsp