correct. It seems that the origin of these samples (group i) is the same as that of the group (ii). All samples are probably iron slag or slag formers which were used for iron production.

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Acknowledgement

This work was partially supported by VEGA 2506025 and KEGA 3/00503.

REFERENCES


Fig. 1 Scheme of experiment: a) for near-field shape measurement, b) for spectral analysis, G-pulse generator, NSOM near-field scanning optical microscopy arrangement, LD-laser diode, LO-Lock: in amplifier, MA-spectral analyzer.
The optical near field of laser diode was recorded using optical fiber-tip mounted on 3D mechanical positioning stage (Near-field scanning optical microscopy - NSOM) with step 50nm. The fiber-tip diameter used for field detection was better than 200nm [4]. The fiber-tip was placed <50nm close to the front laser facet. Two experimental setups were used to analyze the near-field shape of laser device and the laser emission spectra:

![Fig. 2 Detail of NSOM experiment on front laser facet. CH - laser diode chip, FT - fiber-tip, TC - tip contact, BC - bottom contact, W - gain guided waveguide](image)

![Fig. 3 Dependence of optical power vs. driving current with estimated threshold current value Ith=40mA](image)

![Fig. 4 a) Laser mode spectrum at different vertical positions of fiber-tip at driving current 155mA and vertical step 500nm. b) Interpolated density image. Note, zero vertical position doesn't correspond to the middle of active region](image)

![Fig. 5 Measured near-field profile of laser diode in vertical direction (solid line) and integrated near-field profile from measured spectral dependencies approximated with Gaussian curve (dash line).](image)

![Fig. 6 Laser mode spectrum at different driving currents recorded at vertical position +300nm. Additional peaks (add.p.) in spectra are shown.](image)

i) For the near-field shape investigations of laser diode the experimental arrangement with Si-detector has been used (Fig. 1a).

ii) The spectral analysis measurements were investigated using the spectral analyzer Anritsu HS 9710B with spectral range 0.6-1.7µm (Fig. 1b). The spectral analysis using NSOM experiment at different positions of fiber-tip on the front laser facet was determined as is shown on detail scheme of experiment (Fig. 2). The laser mode spectrum has been recorded at different driving currents in stimulated emission. For the spectral analysis using NSOM the following advances were used:

iii) Mode laser spectrum has been recorded at different vertical positions of the NSOM fiber-tip from the front laser facet. Vertical step of experiment was set to 300nm. Horizontal position fiber-tip was set to get the maximal intensity.

iv) Spectral analysis at different driving currents has been taken at defined vertical positions of fiber-tip.

3. EXPERIMENTAL RESULTS

From dependence of optical power vs. driving current the threshold current Ith=40mA has been determined (Fig. 3). The resonator parameters of laser diode are: stripe length d=235µm, stripe width w=2.5µm.

The mode spectrum as well the near-field shape of stripe laser diode has been investigated using NSOM diagnostic and spectral analyzer with spectral resolution 0.07 nm. The measured mode spectrum of laser diode in different vertical position of fiber-tip on the front laser facet with step of record 300 nm is shown in Fig. 4a. For these vertical measurements the horizontal position of fiber-tip was set to obtain the maximum intensity of signal. The corresponding density image of mode spectrum distribution scanned vertically across active region is shown in Fig. 4b. The peaks in laser mode spectra correspond to longitudinal modes in the Fabry-Perot resonator. Their wavelength separation could be determined from simple approach for Fabry-Perot resonator:

\[
\Delta \lambda = \frac{2n}{d},
\]

where \( \lambda \) is the wavelength one of adjacent modes, \( n \) is refractive index and \( d \) is resonator length (in stripe laser diode \( d \) is stripe length). The mode separation of the investigated laser diode for adjacent modes (maximum at wavelength \( \lambda = 919.8 \) nm) was determined from measured spectra \( \Delta \lambda = 0.5 \) nm. This experimental result corresponds to theoretical calculation \( \Delta \lambda = 2.97 \) nm, following equation (1) and taking into account the waveguide parameters of laser diode stripe (length \( d = 235 \) µm and refractive index of active region \( n_{\text{GaAs}} = 3.55 \)).

In all range of vertical scanning only longitudinal modes corresponding to Fabry-Perot wavelengths were observed. From these spectral dependencies scanned along vertical axis of active region the near-field profile was calculated as a simple integration in the wavelength range 915-925 nm in all vertical positions. The calculated near-field profile was compared with measured data scanned in vertical direction using Si-detector. Good agreement of near-field profiles obtained using both of methods is shown in Fig. 5. The weak shoulders on solid curve reflect the fiber-tip surface inhomogeneities originated from the technological imperfections of fiber-tip preparation [5].

In all vertical positions the current dependencies of laser mode spectra were measured. Corresponding current dependencies in vertical position +300nm are shown in Fig. 6. By increasing the driving current the intensity of the longitudinal mode at 919.8 nm increases while the intensity of other modes lightly declines. In these current dependencies the additional peaks (add.p.) have been observed. Their positions in spectral dependencies do not correspond to the longitudinal Fabry-Perot resonator wavelengths. Their behavior as well as their origin will be subject of forthcoming investigations. We suppose their relation with lateral modes of planar waveguide. We believe, that the
The optical near field of laser diode was recorded using optical fiber-tip mounted on 3D mechanical positioning stage (Near-field scanning optical microscopy — NSOM) with step 50nm. The fiber-tip diameter used for field detection was better than 200nm [4]. The fiber-tip was placed <50nm close to the front laser facet. Two experimental setups were used to analyze the near-field shape of laser device and the laser emission spectra:

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- The spectral analysis using NSOM experiment at different positions of fiber-tip on the front laser facet was determined as is shown on detail scheme of experiment (Fig. 2). The laser mode spectrum has been recorded at different driving currents in stimulated emission. For the spectral analysis using NSOM the following advances were used:
  - Mode laser spectrum has been recorded at different vertical positions of the NSOM fiber-tip from the front laser facet. Vertical step of experiment was set to 300nm. Horizontal position fiber-tip was set to get the maximal intensity.
  - Spectral analysis at different driving currents has been taken at defined vertical positions of fiber-tip.

### 3. EXPERIMENTAL RESULTS

From dependence of optical power vs. driving current the threshold current \( I_{th} = 40\text{mA} \) has been determined (Fig. 3). The resonator parameters of laser diode are: stripe length \( d = 235\mu m \), stripe width \( w = 2.2\mu m \).

The mode spectrum as well the near-field shape of stripe laser diode has been investigated using NSOM diagnostic and spectral analyzer with spectral resolution 0.07 nm. The measured mode spectrum of laser diode in different vertical position of fiber-tip on the front laser facet with step of record 300 nm is shown in Fig. 4a. For these vertical measurements the horizontal position of fiber-tip was set to obtain the maximum intensity of signal. The corresponding density image of mode spectrum distribution scanned vertically across active region is shown in Fig. 4b.

The peaks in laser mode spectra correspond to longitudinal modes in the Fabry-Perot resonator. Their wavelength separation could be determined from simple approach for Fabry-Perot resonator:

\[
\Delta \lambda = \frac{\lambda^2}{2d},
\]

where \( \lambda \) is the wavelength one of adjacent modes, \( n \) is refractive index and \( d \) is resonator length (in stripe laser diode \( d \) is stripe length). The mode separation of the investigated laser diode for adjacent modes (maximum at wavelength \( \lambda = 919.8\text{ nm} \)) was determined from measured spectra \( \Delta \lambda = 0.5\text{nm} \). This experimental result corresponds to theoretical calculation \( \Delta \lambda = 0.507\text{nm} \), following equation (1) and taking into account the waveguide parameters of laser diode stripe (length \( d = 235\mu m \) and refractive index of active region \( n_{GaAs} = 3.55 \)).

In all range of vertical scanning only longitudinal modes corresponding to Fabry-Perot wavelengths were observed. From these spectral dependencies scanned along vertical axis of active region the near-field profile was calculated as a simple integration in the wavelength range 915-925 nm in all vertical positions. The calculated near-field profile was compared with measured data scanned in vertical direction using Si-detector. Good agreement of near-field profiles obtained using both of methods is shown in Fig. 5. The weak shoulders on solid curve reflect the fiber-tip surface inhomogeneities originated from the technological imperfections of fiber-tip preparation [5].

![Fig. 4 a) Laser mode spectrum at different vertical positions of fiber tip at driving current 15.50mA and vertical step 300nm. b) interpolated density image. Note, zero vertical position doesn't correspond to the middle of active region.](image)

In all vertical positions the current dependencies of laser mode spectra were measured. Corresponding current dependencies in vertical position +300nm are shown in Fig. 6. By increasing the driving current the intensity of the longitudinal mode at 919.8 nm increases while the intensity of other modes lightly declines. In these current dependencies the additional peaks (add.p.) have been observed. Their positions in spectral dependencies do not correspond to the longitudinal Fabry-Perot resonator wavelengths. Their behavior as well as their origin will be subject of forthcoming investigations. We suppose their relation with lateral modes of planar waveguide. We believe, that the
spectral analysis using NSOM diagnostic in the horizontal direction could reveal more about their origin.

4. CONCLUSION

To our knowledge we employed the local spectral analysis with NSOM diagnostic for the first time as the optical tool for the near-field characterization of laser devices. This method shows the intensity as well as the spectral distribution in different positions of the NSOM fiber-tip in the laser near-field. These results could reveal the longitudinal and lateral modes behavior and could give the complex waveguide characterization in the stripe laser device.

Acknowledgement

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REFERENCES


NANOTUBES AS COLD CATHODE ELEMENTS

Jan Janik, Peter Vindoška, Marian Marton

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Summary

Several materials have been developed, investigated and have exhibited various emission properties following the intent to use them as cold cathodes. The most significant steps in the development of such materials were probably diamond/DLC thin films and nanotubes. These steps are indicating the chronology in the process of preparation and investigation of properties of various materials at the Department of Microelectronics, SUT in Bratislava [11][12][14][15][16]. Recent experiments exhibit emission currents approximately 1,105 mA/cm² at 6,205 V/m for nanotubes grown on copper plate.

1. INTRODUCTION

After some attempts to model electron trajectories in vicinity of an emitting tip [6], other interesting allotrope modification of carbon suitable for cold cathode fabrication - carbon nanotubes were prepared [7] at the department of Microelectronics of Faculty of Electrical Engineering and Information Technology of Slovak University of Technology in Bratislava. It has been also observed, that the current density for metal wire covered nanotube emitters at certain electric field depends on the material of the wire, too [9]. The current density exhibited higher values for nanotubes grown on Fe wire than for nanotubes grown on Ni wire. Nanotubes grow just on (or in vicinity of) catalytic materials, which can be atoms of Fe, Ni, or some other elements. A strong electric field appears in the vicinity of the substance, even when a small voltage difference is applied. On the other hand, Langmuir's law reduces the high current density. But one cannot exclude, that so gently objects could be destroyed by the current density even in this case.

2. EXPERIMENTAL

The nanotubes were prepared on various metal substrates by HF CVD in a vacuum chamber. The simplified diagram of the HF CVD vacuum apparatus is on figure 1. The substrate consisted of metal plates, which were aligned one on the top of another. The pressure in the vacuum chamber was 3 kPa, while the temperature of the substrate was varying between 600 and 650°C. Nanotubes grew in a 1% mixture of methane in hydrogen gas at substrate holder bias of 170V and were found to be grown between the two copper planes, and between the copper plane and the molybdenum substrate holder, too. A surface of Cu plane covered by nanotubes is shown as a result of our experiment on fig 2. The plane dimensions are approximately 1cm x 1cm and its surface is covered by a material seeming like a cotton. The figure is a SEM microscope image and the white areas at the image are places of substance with rather high secondary emission coefficient or a substance with low work function. Emissive characteristics were measured under pressure better than 1.10⁻³ Pa in a measuring chamber. The measuring chamber was pumped with a rotary pump (VRO 15-20), and a turbomolecular pump (Pfeiffer Balzers TPU 330). The distance between the cathode and the anode was 0.68 mm. A voltage was applied over the cathode and the anode and the current was measured.