Measurement of Semiconductor Surface Temperature Using Raman Spectroscopy

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ABSTRACT Temperatures in minute regions of semiconductor devices have been measured using Raman spectroscopy. The temperature of the emitting portion of a 1480-nm InGaAsP semiconductor laser manufactured by Furukawa Electric and having the world's highest output power has been measured. By means of comparison with InGaAs/GaAs lasers, it has been shown that InGaAsP lasers exhibit excellent resistance to catastrophic optical damage resulting from heat.

In another application, the temperatures of MESFETs were also measured, demonstrating that there is a temperature distribution even within the 5-μm distance between source and drain, and that there is a marked temperature rise from the gate. In addition it has been demonstrated that temperature measurement using Raman spectroscopy offers extremely high area resolution.

1. OBJECTIVE

As electro-optical semiconductor devices become smaller, the actual operating region within the device shrinks to the micron or submicron order. Since the electrical power consumed in the device is concentrated in this minute space, there is considerable heat generated in the operating region.

Heat causes degradation of the inherent properties and reliability of the device. Devices that handle high power are particularly subject to demands for high-power handling, and due to device miniaturization, confront the most acute problem.

The direct means of clarifying the cause of heat generation is to measure temperature, but in micron-order areas, ordinary techniques of temperature measurement cannot be used.

The present work aims at measuring temperatures near the surface in minute regions of semiconductors, and for this purpose adopts the technique of Raman spectroscopy, which not only makes possible the measurement of temperatures in minute regions but also allows measurements to be made when devices are in operation, without contact and without damage[1)].

As an example, the results of measuring temperatures at the emitting facet of a semiconductor laser and in the vicinity of MESFET gates are reported. In the case of MESFET temperature, measurement with area resolution of the submicron order was achieved.

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2. MEASUREMENT METHODOLOGY

The heat-generating portion of the semiconductor laser described here was several micrometers in diameter, and that of the MESFET measured several micrometers by several hundred micrometers. Both had regions that could be called minute--several micrometers in size. Thus measurement with an area resolution of 1μm or less was required.

Research on techniques for measuring temperatures in minute regions is on-going, and no specific method has yet been established[2)~4)]. The problem bedeviling the development of such technology is the need to measure minute amounts of heat in minute regions. Even though the energy density in the heat generating region may be high, the small size of the region means that the total heat produced is small.In contact-type measurement of heat, as in a thermocouple, heat flows into the measurer (the thermocouple) damaging its actual operating state.

Noncontact methods of temperature measurement include measurement of black-body radiation in the infrared range, but the most commonly used infrared wavelengths are from several micrometers to several tens of micrometers. Area resolution is limited by wavelength and is thus several micrometers at best, and accuracy is further limited by the optics, so that the limit of area resolution is around 5μm.

Thus we see that the essential conditions for the measurement of the temperature of a semiconductor device in operation are to be noncontact, to not damage the operating state, and to give high area resolution.

Raman spectroscopy provides noncontact temperature measurement, and when light in the visible short wavelength from an Ar or He-Ne laser is used as the stimulating light, area resolutions of 1μm or less can be obtained. Today's measurement systems can effect measurement even at a stimulating light intensity in the order of 1 mW, and are unlikely to alter the operating state of the device.

For these reasons we have conducted experiments on the use of Raman spectroscopy in measuring temperatures in minute areas of semiconductors.

3. RAMAN SCATTERING AND TEMPERATURE MEASUREMENT

Raman scattering is a phenomenon whereby, when a specimen is irradiated with (monochrome) light, the energy of the photons of the irradiating light undergoes nonelastic scattering due to lattice vibration specific to the material of the specimens, so that the frequency of the irradiating light shifts by an amount equivalent to the lattice vibration frequency.

Figure 1 shows the Raman spectrum from the (110) surface of GaAs. There are two types of Raman scattered light: Stokes, with a Raman light frequency of (ω_i-ω_μ), and anti-Stokes, with a Raman light frequency of (ω_i+ω_μ), where ω_i is the stimulating light frequency and ω_μ is the lattice vibration frequency. In Figure 1, the ω_μ for GaAs is 268 cm^{-1}.

To evaluate the temperature of a substance using Raman scattering, we may use the formula[5)]

$$\exp\left(-\frac{hc\,\omega_\mu}{k_B T}\right)=\frac{I_{AS}(\omega_\mu)/(\omega_i-\omega_\mu)^4}{I_S(\omega_\mu)/(\omega_i+\omega_\mu)^4} \qquad (1)$$

where: I_{AS} and I_S are the intensities of the anti- Stokes and Stokes scattered light, and T is the temperature of the specimen.

In substance, the specimen temperature determines the ratio between the intensities of anti-Stokes and Stokes scattered light. The lattice vibration frequency to be measured is specific to the substance, and does not depend on the wavelength of the stimulating light.

Measurement is done by means of an ordinary Raman spectroscopy microscope. The stimulating light is from an Ar laser with a wavelength of 514.5 nm. The laser light is irradiated onto the specimen through a half mirror and the microscope objective lens. The diameter of the stimulating light on the sample is thus the same as the area resolution, and area resolution may be improved by focusing the stimulating light using a higher-power objective lens. The objective lens used was 100-power, and this yields a focal diameter of approximately 0.5μm.

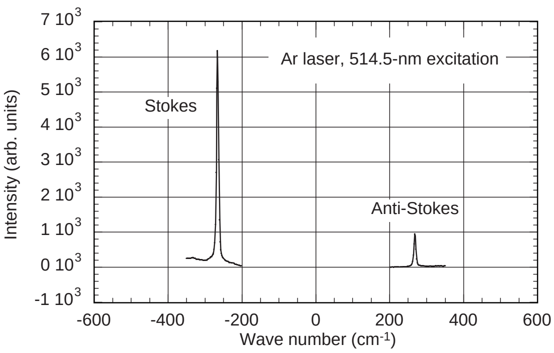

Figure 1 Raman spectrum from the GaAs (110) surface

The Raman scattered light that is emitted from the specimen in the opposite direction to the stimulating light is once more passed through the objective lens and the half mirror before entering the spectroscope. The spectroscope consists of a triple monochrometer, with provision made so that the weak Raman light is not blotted out by background light. Light emitted from the spectroscope goes to a detector, where the Raman light is measured.

To keep the specimen at constant temperature, the specimen stage is temperature-controlled by a Peltier device. To measure the surface distribution of device temperature, a movable X-Y-Z stage is provided, the movement of which can be set at the submicron level.

4. TEMPERATURE MEASUREMENT

4.1 Temperature Calibration

Before measuring the temperature of a device, measurements were made using a GaAs substrate.

Since in Raman microscopy the stimulating light is focused on the specimen, heating will occur at the focal point in materials that absorb the stimulating light. Since this constitutes measurement error at the point of measurement, the tendency must be investigated in advance.

Figure 2 is a graph showing the relationship between the intensity of the stimulating light from an Ar laser and the temperature as measured by Raman spectroscopy. The specimens used were (100) GaAs substrates. The substrate was connected to a Peltier device via a heat sink to maintain a temperature of 25°C. As can be seen, the measured temperature was substantially constant at 25°C when stimulating light power was 5 mW or less. That is to say, if the effect of temperature rise due to stimulating light is to be ignored, stimulating light power should be set at 5 mW or less.

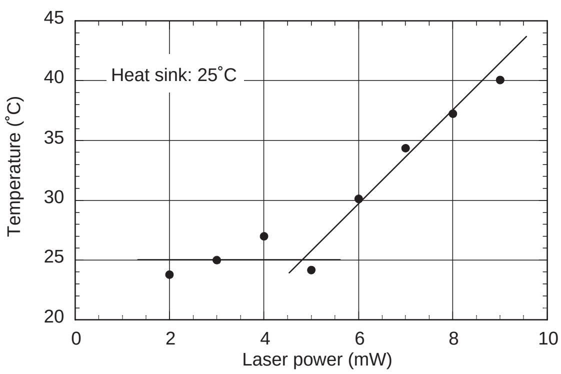

Figure 2 Increase in measured temperature on the surface of GaAs substrates irradiated by Ar laser

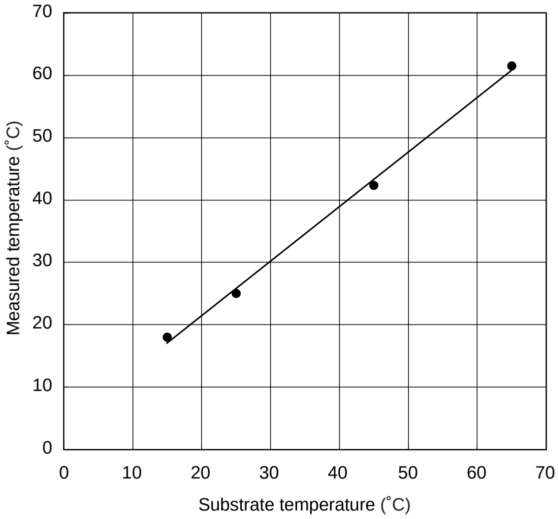

Figure 3 GaAs substrate temperature vs. the value measured by Raman spectroscopy

At 5 mW or more, the measured temperature rose in direct proportion to the increase in stimulating light power. In this power region, the stimulating light injected exceeded the heat-absorbing capacity of the Peltier device. The slope of the graph is equivalent to the thermal resistance between the point of measurement and the heat sink, or approximately 4 K/mW.

In this example the boundary at which the effect of temperature rise due to stimulating light was at 5 mW, but this will vary somewhat according to the thermal resistance of the specimen. Actual measurements were made at a stimulating light power of several milliwatts.

Figure 3 shows the results of temperature measurements made while the temperature of the specimen as a whole was changed by means of the Peltier device. Substrate temperature shows good agreement with the measured temperature, demonstrating the feasibility of temperature measurement using Raman spectroscopy.

In Figure 3, the temperature measurement error was not more than ±3°C. And as a result of long-term temperature calibration, a temperature measurement error of ±5°C has been achieved.

4.2 Measuring the Temperature of the Emitting Surface of a Semiconductor Laser

The pumping light source used for the optical fiber amplifiers that have significantly increased the range of fiber-optic communications is a 1480-nm high-power semiconductor laser. Furukawa Electric manufactures the world's highest-power 1480-nm semiconductor laser, providing an emitting power of 180 mW.

To improve emission efficiency and fiber coupling efficiency, the emitting region is only a few micrometers in diameter, and when the optical power is thus concentrated in such a small region, it becomes hot, reducing emission efficiency and reliability.

Temperature measurements were carried out by Raman spectroscopy to investigate how much heat is actually generated at the emitting facet.

Figure 4 shows the injection current I_{inj} and emitting region temperature of a 1480-nm semiconductor laser. It can be seen that at an injection current of 400 mA there is a temperature rise of 35°C, and that the temperature of the emitting region increases substantially in proportion to I_{inj}. The lasing threshold current I_{th} is 30 mA, and at I_{th} and above, the light output is proportional to (I_{inj}-I_{th}). When I_{inj} is considerably greater than I_{th} (i.e., several hundred milliamperes), it may be taken that the light output is substantially proportional to I_{inj}. With an injection current of approximately 400 mA, the light output of the 1480-nm semiconductor laser is 140 mW, so that at a light output of 140 mW, the temperature of the emitting region increases in proportion to the light output. The gradient of the temperature rise of the emission region relative to light output may be estimated as 0.2 K/mW for the chips measured.

Since this paper is the first to report on facet temperature measurements in 1480-nm semiconductor lasers, there is no standard against which to judge whether the results are superior or not. Accordingly a comparison is made with reports on GaAs/AlGaAs and InGaAs/AlGaAs semiconductor lasers[6]. The rates of temperature rise were 1.6 and 0.3 K/mW, respectively. In all cases a situation conducive to rapid degradation was intentionally arranged by not providing a protective film of the emitting facet.

Comparing Furukawa Electric's 1480-nm laser, its rate of temperature rise was not as high as the GaAs-based laser, but was about the same level as the InGaAs. The InGaAs-based laser referred to above degraded rapidly but the InGaAsP-based 1480-nm laser measured on this occasion did not exhibit rapid degradation, and reliability was adequate to allow use in repeaters for submarine optical fiber cables.

Thus we may say that the InGaAsP-based laser showed stronger resistance to emission region temperature rise than did InGaAs/GaAs-based lasers.

The degradation mode in the GaAs- and InGaAs-based lasers referred to above occurred when operating under automatic power control (APC), in which light power is held constant. This is known as the catastrophic optical damage (COD) mode, in which the rise in emitting region temperature leads to a drop in emission efficiency and the flow of injection current to the laser increases, until feed-

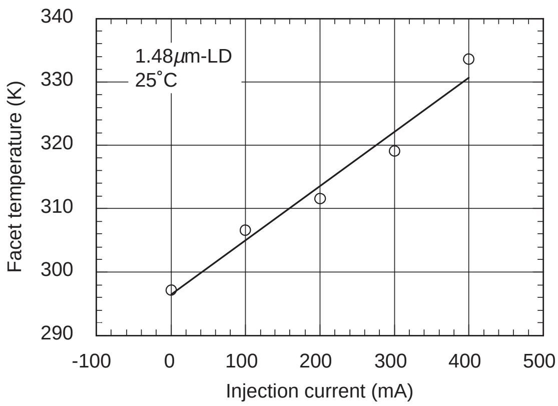

Figure 4 Facet temperature vs. injection current of a 1480-nm high-power laser at a heat sink temperature of 25°C

back that causes further temperature increase results in fusion of the emitting region. To analyze this phenomenon requires analysis of emitting region temperature, and the technique of temperature measurement using Raman spectroscopy that is introduced here will also prove useful in COD analysis.

4.3 Measuring the Temperature of MESFETs

MESFETs are unipolar transistors consisting primarily of Group III-V compound semiconductors. Since the mobility of compound semiconductors is greater than that of Si, MESFETs are used in such high-speed applications as companders in satellite broadcasting and transceivers in cellular telephones.

Figure 5 shows a top view of a typical MESFET, in which current flows in a channel formed between the source (S) and drain (D) electrodes. The gate (G) electrode is between the semiconductors having a Schottky junction, controlling the current in the channel beneath the gate.

MESFETs are high-speed devices, but speed may be further increased by shortening gate length in Figure 5. To reduce the parasitic resistance component, the distance of the S-G and D-G gaps may also be reduced. These distances are in the order of 1μm or less.

MESFETs are generally used with the source electrode referenced to 0 V and drain positive and the gate in the vicinity of 0 V or negative bias. In this bias state, a high reverse-bias is applied between drain and gate. Thus the potential gradient between drain and gate is largest in the channel between source and drain, and virtually all of the injected power is dissipated here. This, then, is considered to be the point at which heat is generated.

This heat--what is known as the junction temperature--is an important factor in determining the reliability time in the design of circuits using MESFETs.

In a report on the measurement of heat generated in MESFETs using infrared thermography[2)], the heat generation point was identified as being near the gate electrode, but since area resolution was 5μm, it was impossible to specify whether it was at the drain or the source. Accordingly we measured the temperature distribution in MESFETs using Raman spectroscopy.

The MESFETs used consisted of a GaAs substrate on which a GaAs channel was grown epitaxially. To define the region of a single MESFET, the outside of the rectangular area on the top surface denoted as a mesa in Figure 5 was etched and the channel was removed from the mesa area.

The electrode arrangement of the MESFETs measured was similar to that shown in Figure 5, with an S-G gap of 2μm, gate length of 1μm and D-G gap of 2μm. Gate width was 100μm, but by wiring another FET in parallel with this one, a 2-finger gate structure was created, with an equivalent gate width of 200μm. Measurements were carried out in the vicinity of one of these gate electrodes. The points of measurement were along line A-A' in Figure 5.

Electrically speaking, measurement conditions were V_{ds} = 4 V and V_{gs} = 0 V, with a drain current I_d of 40 mA. Measurements were also made at zero bias (V_{ds} = 0 V). MESFET temperature was kept at 25°C by means of a Peltier device.

Figure 6 shows the result of temperature measurements across the gate (direction A-A' in Figure 5). The horizontal axis represents the distance in the direction of the gate referenced to the end of the electrode. The difference in temperature measurements immediately before and after application of bias to the drain was defined as the temperature rise, and this is shown on the vertical axis in Figure 5.

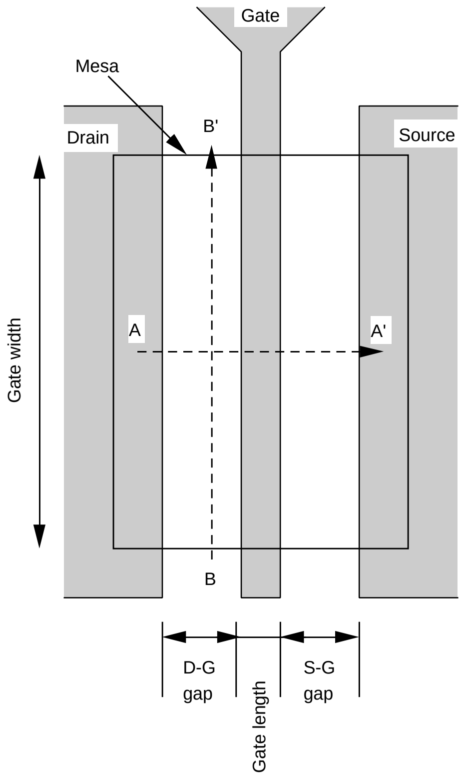

Figure 5 **Top view of MESFET (temperatures were measured along the dotted lines)**

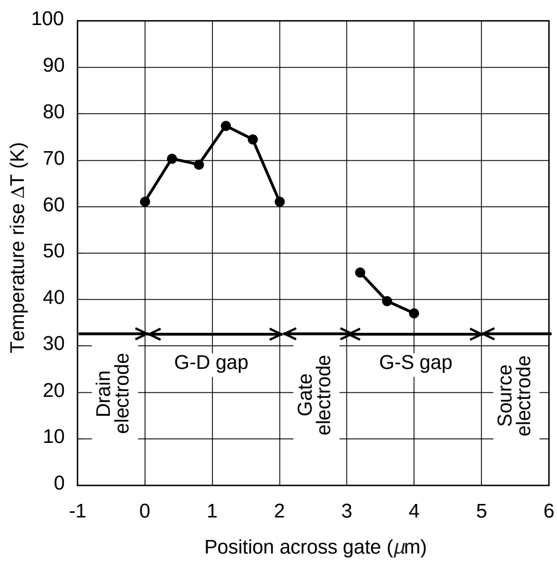

Figure 6 **Temperature distribution across MESFET gate electrode along line A-A' in Figure 5**

From Figure 6 it can be seen that the rise in temperature peaked at about 80°C. The temperature rise between source and gate was about 40°C greater than the drain-to-gate value. By means of the high-accuracy movable stage, temperature measurements were carried out with 0.4-μm pitch positional resolution, so that it was possible to examine the D-G gap in detail and even to confirm that the peak in temperature rise was closer to the gate than to the drain. In this device the source-to-drain distance was only 5μm so that measurements using apparatus with an area resolution of about 5μm would average the temperatures in this area. In the example shown in Figure 6, for example, a temperature rise of 50-60°C was measured, differing by 20-30°C from the results of 80°C obtained in the present work. Thus the existence of a temperature distribution in the mere 5μm between source and drain, demonstrates the great utility of Raman spectroscopy used in this study in the measurement of temperature rise peaks.

The results obtained were then compared with those reported elsewhere. It is thought that the power dissipated between drain and gate is distributed uniformly along the direction toward the gate, or put another way, temperature rise is a function of power dissipation per gate. If the power dissipation per unit gate width is calculated for the MESFETs measured in this work, the result is 0.8 mW/μm. Since this was accompanied by a temperature rise of approximately 85°C, the temperature rise per unit gate width is 110 K/(mW/μm).

Similarly examining the data from the literature[2], there was a temperature rise of approximately 50°C against a power dissipation per unit gate width of 0.46 mW/μm, yielding a temperature rise rate of 110 K/(mW/μm)--the same value obtained in the present work. However since reference 2) uses infrared thermography, it is possible that the measured temperatures have been averaged out. Thus it was realized that the temperature rise rate in the MESFETs measured in this work was the same as or lower than that obtained in the literature cited.

5. CONCLUSION

Raman spectroscopy was examined as a method of measuring the temperature of minute regions of semiconductor devices, and as a result of carrying out temperature calibration, a measuring accuracy of ±5°C was achieved over the long term.

The method was applied to actual devices. The temperature of the emitting region of Furukawa Electric's 1480-nm InGaAsP lasers, which have achieved the highest output power in the world, was measured. The results showed that the temperature rise per unit output power was approximately 0.2 K/mW, and it was demonstrated that the InGaAsP lasers had higher resistance to catastrophic optical damage (COD) than did devices based on InGaAs/GaAs.

As another device application, MESFET temperatures were also measured. As a result of linear analysis carried out at 0.4-μm pitch, it was found that there was a temperature distribution even over the minute separation of 5μm between source and drain. It was shown by actual measurement that this temperature rise was particularly marked toward the gate. In addition it was demonstrated that temperature measurement using Raman spectroscopy had extremely high area resolution.

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