MICROCHANNEL GATE TEMPERATURE ANALYSIS

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Abstract

Photoemission spectra of a GaAs gate material of a metal semiconductor field effect transistor (MESFET) were analyzed to nondestructively assess the submicron-size local gate temperature. Utilizing the micromanipulator, the laser beam was precisely adjusted to probe the exact position of the device gate. The emission spectral bands due to the interaction among photons, free excitons and impurity bound excitons in GaAs gate materials were measured and identified both at 299.1 K and 84.8 K. The shift of the band was found to be 16.30 meV for the free excitons when the device was not powered, while the band shift of the gate was 7.38 meV when the device was powered at 84.8 K. Simple first order calculations based on the theory of temperature shift of the bound excitons, predicts an inversely proportional relationship between the emission bandshift and temperature. Measurements using this technique found an increase of 97.0 K.

Introduction

There is a growing interest in semiconductor materials and devices for high temperature, high power, and high frequency applications. However, the reliability of the devices for long term applications has been a concern. Thermal and mechanical failures on ICs in interconnect metallization and multilayer structures of advanced microelectronic devices have been recognized in the application of many NASA and DoD space projects for the past decade. Thermal degradation induces electrical and mechanical stress on power transistors and precise knowledge of the local channel temperature of a GaAs Power MESFET during operation is critical to determining expected lifetime and overall device reliability.

The polarized liquid crystal technique, which is destructive, has been utilized for estimating device temperatures with a spatial resolution of about 1 µm. On the other hand, non-destructive passive infrared temperature measurement techniques provide temperature measurements with a spatial resolution of 15 µm, which is too coarse for determining local distribution of state-of-the-art microelectronic device temperatures with submicron gate structures.

An alternative optical technique based on infrared emission spectroscopy was developed to provide high resolution, non-destructive channel temperature measurements of the hot spot in the gate channel of a GaAs MESFET.

Band shifts and broadening of solid state semiconductor device materials due to temperature variation has been well understood in principal. The thermal shift of a spectral line is the statistical algebraic sum of the shifts of the two levels involved in the transition allowed by the selection roles as shown in equation (1).

$$\delta E_i = \Sigma_j (<i|H'|j><j|H'|i>)/(E_i - E_j)+<i|H''|j>, \qquad (1)$$

Where

$$H' = iV_1 \Sigma_q (h\omega_q/4\pi Mv^2)^{1/2}(b_q - b_q^+),$$

$$H'' = - V_2(h/ 4\pi Mv^2)\ \Sigma_{qq'}(\omega_q\, \omega_{q'})(b_q - b_q^+)(b_{q'} - b_{q'}^+),$$

$$H = H_{latt} + H_{ion,exc} + H_{int}$$

$$H_{latt} = \Sigma_k (h\omega_k)^{1/2}(a_k a_k^+ + 1),$$

$$H_{ion,exc} = H_o + H_{cryst} + H_{so},$$

$$H_{int} = V_1\varepsilon + V_2\, \varepsilon^2 + ...,$$

$$\varepsilon = iV_1 \Sigma_q (h\omega_q/4\pi Mv^2)^{1/2}(b_q - b_q^+),$$

a_k, b_q, and a_k^+, b_q^+: annihilation and creation operators of photons and phonons.

However, the crystalline field at the ion, varying in time with the thermal lattice vibrations (phonons) of the neighboring ions, sets up an interaction between the ionic system and the normal modes of the lattice vibrations in the semiconductor lattice. The ionic system includes the neutral excited mobile states (excitons) of a crystal bound to neutral donors and acceptors. Such interaction information obtained from spectral lines has been used in the past to explain the temperature dependence of the relaxation time of crystal ions in semiconductor band structures, as shown in Figure 1. The width of a spectral line is the statistical sum of the energy spread of the two energy levels involved and may also be broadened by the same mechanisms. [1-3]

Many reports have appeared identifying various photoluminescence (PL) emission characteristics in GaAs multiple-quantum well devices. The spectral characteristics involving the intrinsic and extrinsic radiative recombination of free excitons have been well established to explain the device material quantum-well structures. The intrinsic emissions of the excitons have been observed even at room temperature as dominant radiative transitions. [4-5] The temperature dependence PL spectra of many different GaAs devices can be found elsewhere. [6-7]

One of the many practical applications of this spectral dependence of band shifts and broadening of device materials upon device temperatures is to predict the temperature of a powered device by calibrating an unpowered device at different controlled temperatures. The true operating temperature of the micron-size powered GaAs MESFET local channel can then be found by measuring the shifts of the spectral band of the multi-quantum well devices.

In this paper we describe the novel, nondestructive experimental procedures for channel temperature measurement and then discuss the results of the actual measurements to summarize our conclusions.

Experimental

The thermal dependence on PL from semiconductor material has been well understood in principle, but it has been difficult to utilize optical techniques to measure the emission spectrum from a fabricated device until the advancement of optical manipulation techniques and computer image processing technology. The technology can now precisely locate a one-micron diameter exciting laser beam, such as a helium-neon laser, on a position of IC components that is most vulnerable to thermal degradation due to high power or stress. The PL light collected nondestructively from a specific component of a fabricated device can then supply information of the device, including the temperature profile of the device component.

The method utilizes the latest optical manipulating system, triple grating spectrophotometer technology and up-to-date computer image processing techniques to precisely locate the emission source of the ICs most vulnerable to power system operation. A dual micromanipulator is coupled to a thermoelectrically cooled photomultiplier tube (PMT), wavelength scanning system, and conventional lock-in amplifier to detect and amplify the extremely fine device response or photoluminescence (PL) light of the IC gate materials. Computer data processing techniques were employed to boost system sensitivity for signal analysis.

Figure 2 shows a diagram of the PL measurement system. The technique uses a well-focused incident laser beam to generate electron-hole pairs in the semiconductor gate material.

The basic setup consists of three major parts: (a) an optical probing stage with a microscope, (b) a gated monochromatic-intensifier with a cooled photomultiplier tube and, (c) data processing and control computer. The micromanipulator adjusts a specific gate portion of a device under test onto the miniaturized focused probing helium-neon ion laser beam. This allows the illuminating photons to excite the valance band electrons to conduction bands in the active channel of the GaAs MESFET. Some of the free electrons and holes will bind together to form excitons near the doping ions next to the conduction bands. Some of these impurity bound excitons will be de-excited into the valence band by interacting with the excitons and the lattice phonons. When this transition occurs the photons will be emitted in all directions. The spectrophotometer monitors the emission spectrum modulated by the excitons near to the conduction bands. The emission exciton bands will be modulated by the lattice phonons, which represent the temperature information of the microelectronic device under tests. The spectrophotometer used for these tests was Jarrell-Ash Monspec 27. Thermoelectrically cooled photomultiplier tube (Hamamatsu R943-02/RCA 31032) was used for the detection of the spectrophotometer. The detected signal was preamplified by an Ithaco Model 164 prior to being fed into an Ithaco Dynatrac 393 Lock-In amplifier. The whole system was controlled by a personal computer. This system was also equipped with an electronic strobing or grating capability, so that it could determine the timing of the device performance and band edges of optical emission.

A micromanipulator stage with a resolution of 0.1 μm was used to position the device under test so that the laser beam exclusively impinges at the desired position of the device. Light emitted from the illuminated spot on the device was reflected by a beam splitter to a chopper and then focused onto the spectrometer slit. The light signal was also low-pass filtered to discriminate against illuminating laser wavelength. The output of the lock-in amplifier is digitized, and then processed in a personal computer to obtain the spectrum of infrared emission stimulated by the laser beam.

The GaAs power MESFETs (see Figure 3) used for this investigation were mounted on Cu/W carrier, and the JPL hybrid laboratory bonded the wires for controlling gates and power supply.

Results and Discussion

The emission spectrum of GaAs gate material of commercially available GaAs MESFETs was reproduced to identify the reported donor bounded exciton bands with no power applied, at temperatures of 84,8 K and 299.1 K. Not shown in Figure 4, the emission peak at wavelength of 1.41373 eV for the higher temperature (299.1 K) exceeded that (1.43003 eV) for the lower temperature (84.8 K) by about 16.30 meV.

In another measurement run of the same setup, indicated in the Figure 4, the exterior of the device was maintained at 84.8 K and power was applied; the emission peak of 1.42265 eV for this case was shifted by 7.38 meV from the zero power case at 84.8 K. By linear extrapolation, this wavelength shift indicates that under power, the temperature of the gate rose about 97.3 K above the device operating temperature of 84.8 K.

The obtained results were in general agreement with theoretical calculations [1-4] using equation (2), which is derived from equation (1):

$$\mathbf{E_{cv}(T) - E_{cv}(T_o) = -\alpha(T+\beta)} \qquad (2)$$

where,

T = Channel Temperature

T_o= Operating Temperature

E_{cv}= Energy Bandgap

α = Slope of the Extended Plot (Fitting Parameter)

β = Debye Temperature (Fitting parameter).

The test system constructed, which utilized the general setup of these tests and some of the equipment used in the Microelectronic Advanced Laser Scanner (MEALS), was reported elsewhere[8]. Utilizing the micromanipulator stage, a He-Ne laser beam (λ=6238 Angstrom) with a beam diameter of 0.9 microns was precisely adjusted to the exact gate position (resolution less than 0.1 μm) of the GaAs MESFET device. Discriminating emission light signal from the illuminating light was achieved by placing a low-band pass filter between the reflecting mirror (beam splitter) and the spectrometer, as shown in Figure 2. A lock-in amplifier, equipped with a cooled photomultiplier tube, was used for the detection of standard synchronous signals. Data collection and manipulation was performed using a personal computer with the appropriate software tools.

A commercially available GaAs MESFET, with gate dimensions of 0.5 micron (refer Figure 3), was mounted in the test fixture and emission spectra were successfully obtained. The emission spectrum obtained by this test setup, shown in Figure 4, indicates that this technique can be effectively manipulated to collect extremely faint gate emission spectra. The collected emission spectrum, as shown in Figure 4, from the free excitons were identified and measured at an operating temperature of 84.8 K. The free exciton emission band shift of the unpowered GaAs MESFET gate was calibrated by the two different temperatures of 299.1 and 84.8 K. The shift was 16.30 meV. In order to remotely measure the local temperature rise of the gate due to the device operation, the emission band shift of the same gate from unpowered to powered were monitored at one (84.8 K) of the calibrated low temperatures. The shift was 7.38 meV.

The technique exploits the temperature dependence of the wavelength of the peak of the stimulated infrared emission spectrum. This wavelength increases approximately linearly with temperature – a consequence of the fact that the energy band gap of these semiconductor material decreases with temperature. Thus, if the temperature dependence of this wavelength is known, it can be used to determine the local temperature in the device while operating at various power levels.

It is well known that the emission bandshift of a semiconductor material is inversely proportional to the material temperature [2-7] due to the first approximation of the electron-exciton interaction at this temperature range. Thus utilizing the bandshifts, one can calculate the localized hot gate temperature rise of the powered device under test. Equation (1) and information summarized in Table I reveal that the localized hot gate temperature of the device rose by 97.0 K during the operation at 84.8 K. The temperature rise was also compared with conventional IR measurement technique, which has resolution of between 15 and 100 microns. The average temperature rise with this conventional technique was about 88.8 K. The main diffference probably is due to the size of the measurement objective. The temperature rise measured by the infrared radiation technique is not the true local gate temperature but from the average temperature of the gate and the other part of the devices.

Summary

A novel, optical, non-contact technique for the measurement of the channel temperature of GaAs and other direct bandgap semiconductor was developed. The technique based on infrared emission spectroscopy was demonstrated on commercially available GaAs MESFETs and found to have general agreement with calculated results. Further calibration measurements are necessary in order to arrive at more accurate assessment of the channel temperature based on this technique.

Table I. Summary of band shift data

Test Temp.(K)	Band Position (eV)	Power Applied
299.1	1.41373	No
84.8	1.42265	Yes
84.8	1.43003	No

Gate Temperature Rise

$= T - T_o$

$= (299.1\ \text{K} - 84.8\ \text{K}) \times (1.43003 - 1.42265)/(1.43003 - 1.41373)$

$= 97.0\ \text{K}.$

In this report, a new non-destructive submicron-size spot temperature assessment technique was discussed. A non-destructive submicron-size spot laser beam provided by a He-Ne laser excites an extremely small local area of the gate channel of a GaAs MESFET under various operating conditions. The data collected shows a much higher localized “hot spot” temperature of the device than observed using typical IR techniques. This is due to the high-resolution capabilities of this technique. Given the state of the experimental test system, we estimate a spatial resolution of about 0.9 microns and a spectral resolution of about 0.1 Angstroms. This provides 15 - 100 times finer spatial resolution than can be obtained using the best passive IR systems available. The temperature resolution (< 0.02 K/µm) of this technique depends upon the spectrometer used), and can be further improved.

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Figure Captions:

Figure 1. Direct and indirect band structure of semiconductor device materials, involved in optical emission including photons (ω), Phonons (Ω) and excitons (ω_e).

Figure 2. Diagram of channel temperature measurement system.

Figure 3. Cross-section of a typical GaAs MESFET.

Figure 4. Typical Emission Spectrum of the powered and unpowered GaAs MESFET Gate at 84.8 K.

Figures:

Figure 1.

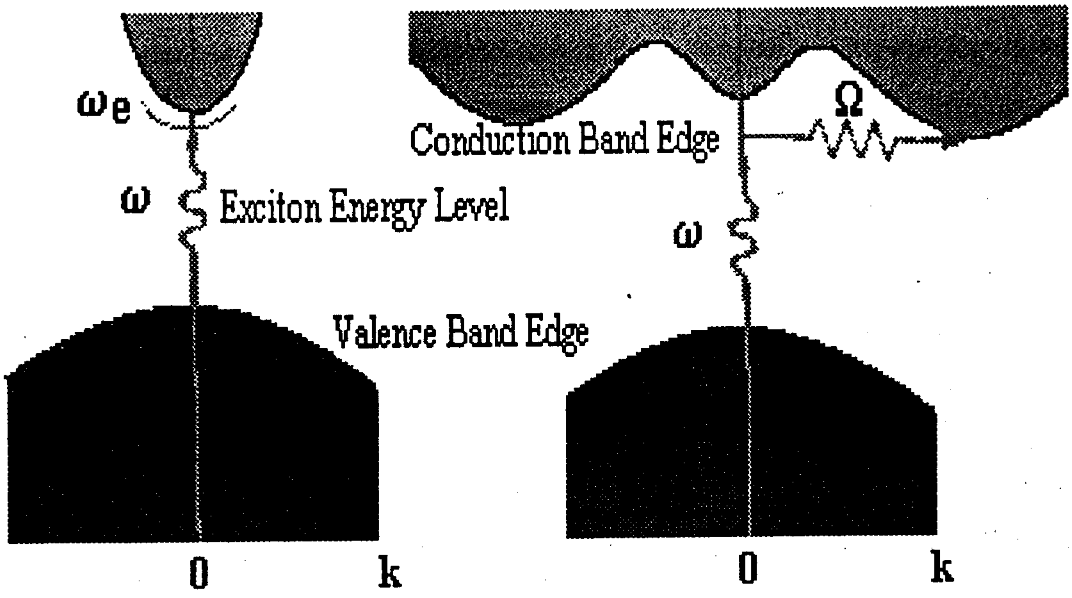

Figure 2.

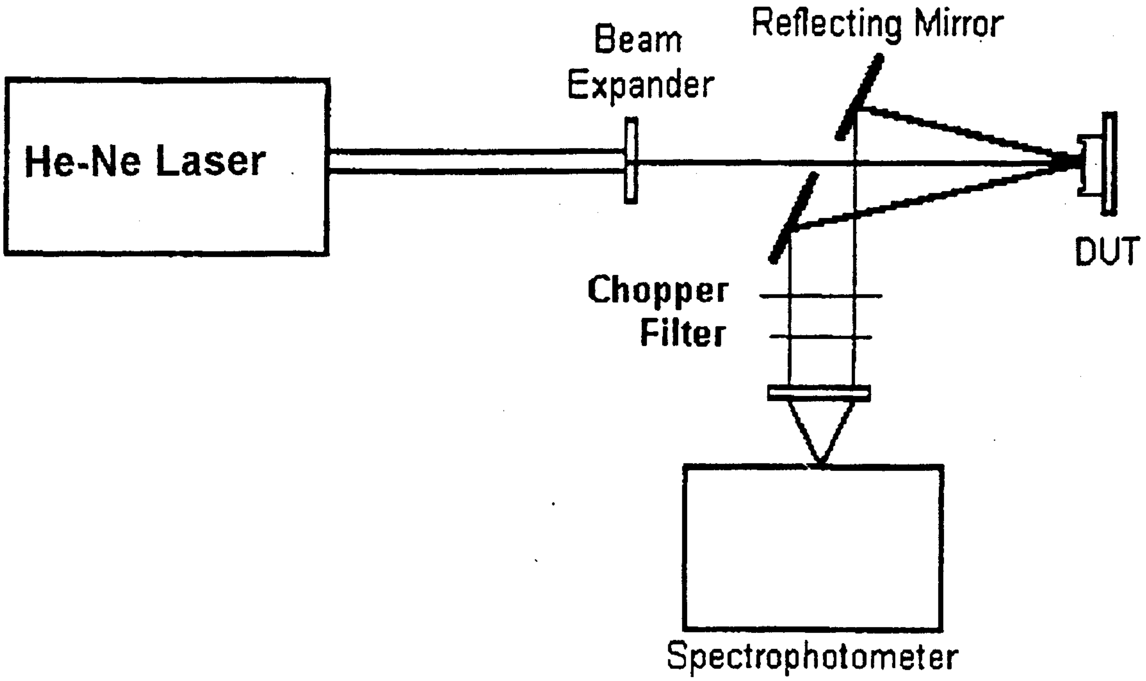

Figure 3.

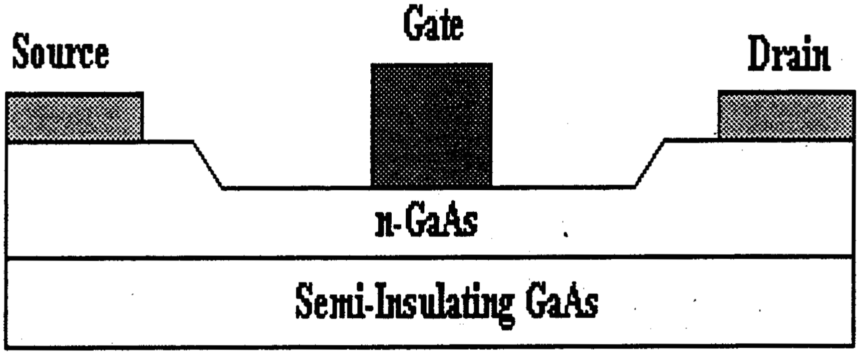

Figure 4.