Determination of channel temperature for AlGaN/GaN HEMTs by high spectral resolution micro-Raman spectroscopy*

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Abstract: Channel temperature determinations of AlGaN/GaN high electron mobility transistors (HEMTs) by high spectral resolution micro-Raman spectroscopy are proposed. The temperature dependence of the E2 phonon frequency of GaN material is calibrated by using a JYT-64000 micro-Raman system. By using the Lorentz fitting method, the measurement uncertainty for the Raman phonon frequency of ± 0.035 cm^{-1} is achieved, corresponding to a temperature accuracy of ± 3.2 ℃ for GaN material, which is the highest temperature resolution in the published works. The thermal resistance of the tested AlGaN/GaN HEMT sample is 22.8 ℃/W, which is in reasonably good agreement with a three dimensional heat conduction simulation. The difference among the channel temperatures obtained by micro-Raman spectroscopy, the pulsed electrical method and the infrared image method are also investigated quantificationally.

Key words: HEMT; channel temperature; micro-Raman spectroscopy
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1. Introduction

Promising higher power densities and better high frequency performance than conventional Si and GaAs technologies, AlGaN/GaN based high electron mobility transistors (HEMTs) will play a central role in future telecommunications and radar applications[1]. However, despite impressive achievements being continuously reported on device parameters in recent years, such as a continuous-wave power density of 41.4 W/mm (on SiC substrate)[2] and 2.9 W/mm at 10 GHz (on (001) silicon substrate)[3], the considerable dissipation power that is concentrated in the sub-micron region leads to a localized high channel temperature. Consequently, careful consideration of the self-heating effect is needed when designing and modeling devices and circuits[4]. Firstly, an accurate measurement of the channel temperature for AlGaN/GaN HEMTs with high spatial and temperature resolution is a crucial task for thermal management and lifetime estimation.

Thermal measurement techniques for semiconductor devices could be categorized as physical contact, optical, and electrical methods[5]. Since the separation between the drain and gate contact, where the joule heat mainly dissipates, is always less than 1 μm for state-of-the-art AlGaN/GaN HEMTs, the physical contact method cannot be used. Because of the relatively lower spatial resolution (5–15 μm), the traditional infrared image method is thought to underestimate the channel temperature. Electrical methods[6] extract the channel temperature rise from the variation of temperature-dependent electrical parameters, and therefore cannot provide spatial temperature distribution. Menozzi *et al*., Kuzmik *et al.*, and Zhang *et al*. reported the channel temperature measurement of AlGaN/GaN HEMTs by selecting the DC drain–source current[7], the output resistance[8] and the forward Schottky characteristics[9] as temperature-sensitive parameters, respectively. In recent years, laser micro-Raman spectroscopy has become a well recognized method to explore the thermal characteristics of semiconductor devices with advantage of high spatial resolution. Kuball *et al.* first reported the channel temperature measurement of GaN heterostructure field-effect transistors (HFETs) by using a Renishaw Raman system with 0.1 cm^{-1} of spectral resolution and 10 ℃ of temperature resolution[10, 11]. By using micro-Raman spectroscopy, Aubry *et al.* optimized the device layout of AlGaN/GaN HEMTs with silicon and sapphire substrates[12, 13], and Kosaka *et al.* analyzed the thermal characteristics of AlGaN/GaN HFETs operated at around breakdown voltage[14]. However, the relatively lower temperature resolution is still the main drawback for the practical application of micro-Raman spectroscopy.

In this paper, we present the determination of channel temperature for AlGaN/GaN HEMTs by high spectral resolution Raman spectroscopy. The measurement is carried out on the AlGaN/GaN HEMT in $z(x, z\text{-})$ backscattering geometry using a JYT-64000 micro-Raman system. The spectral uncertainty of ± 0.035 cm^{-1} is achieved by using a Lorentz fitting process, corresponding to a temperature accuracy of ± 3.2 ℃, which is the highest temperature resolution of channel temperature measurement for an AlGaN/GaN HEMT by micro-Raman spectroscopy in the published works to the best of our knowledge.

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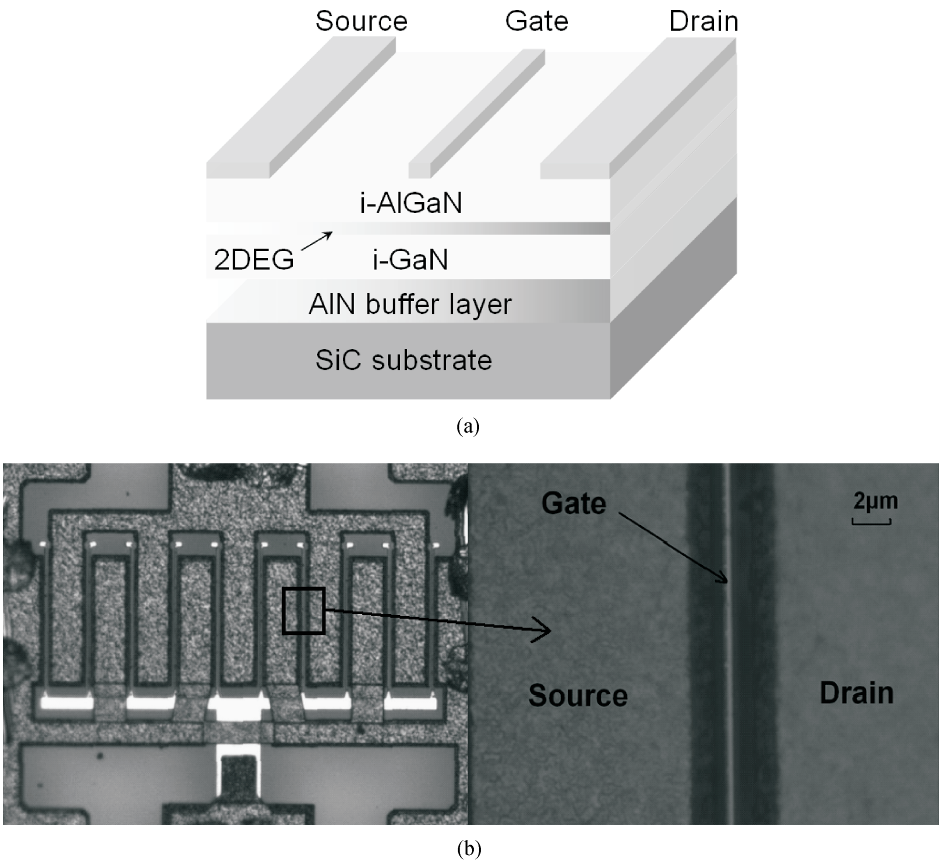

Fig. 1. (a) Schematic and (b) micro-image of the tested AlGaN/GaN HEMTs.

A three-dimensional (3-D) numerical simulation performed by ANSYS is also put forward to verify the measured results by the micro-Raman spectroscopy. In addition, the channel temperatures of AlGaN/GaN HEMTs are also obtained by using a pulsed electrical method and an infrared image method to investigate the difference among these methods quantificationally.

2. Method and experimental apparatus

AlGaN/GaN HEMTs consisting of a 25 nm unintentionally doped AlGaN on a 1.5 μm GaN buffer layer on a 400 μm thick 4H-SiC substrate, with a Ti/Al/Ni/Au drain, source ohmic contacts and a Ni/Au Schottky contact are investigated in this paper. The device is composed of 10 fingers with a gate length of 0.35 μm, a gate width of 100 μm, a source–drain gap of 4.5 μm and a gate–source gap of 1.5 μm. The gate and source contacts are formed by the air-bridge structure. Devices are passivated by a SiN layer of 100 nm. The device structure of the AlGaN/GaN HEMT and micrograph of the chip is shown in Fig. 1.

The concept of temperature measurement of AlGaN/GaN HEMTs by using micro-Raman spectroscopy is based on the temperature dependence of the phonon frequencies of the GaN crystal. Theoretically, temperature (T) could be measured by the Raman phonon frequency and the ratio of the intensities of anti-Stokes (I_{AS}) and Stokes (I_S) lines[15] according to Eq. (1):

$$\frac{I_{AS}}{I_S} = \left(\frac{\omega_l + \omega_p}{\omega_l - \omega_p}\right)^4 \gamma e^{\hbar\omega_p/kT}, \quad (1)$$

where ω_l and ω_p are the frequencies of the laser and the phonons, respectively, γ is a correction coefficient, and $\hbar$ and k have their usual meanings. However, it is difficult to control the measurement accuracy of the ratio of I_{AS} and I_S since the intensities of the anti-Stokes lines are usually much lower than that of the Stokes lines. A practical solution is by using the Cui formula[16], which characterizes the relationship between Raman phonon frequency and the temperature, as shown in Eq. (2):

$$\omega(T) = \omega_0 - \frac{A}{e^{B\hbar\omega_0/kT} - 1}, \quad (2)$$

where $\omega(T)$ is the Raman phonon frequency at temperature T, ω_0 is the Raman phonon frequency at 0 K, A and B are fitting parameters. Therefore, the channel temperature can be obtained by the calibration relationship between the Raman phonon frequency and the temperature.

The measurement is carried out on the AlGaN/GaN HEMT in $z(x,z\text{-})$ backscattering geometry using a JYT-64000 micro-Raman system with the 514.5 nm line of an Ar-laser as excitation source. The diameter of the laser focusing spot is about 1 μm and laser power is approximately 5 mW. No obvious photogenic charge carrier current is observed since the energy of 514.5 nm laser is less than the band gap of AlGaN and GaN materials. The temperature increase induced by the 5 mW laser illumination could also be neglected compared with the watt-level electrical dissipation power.

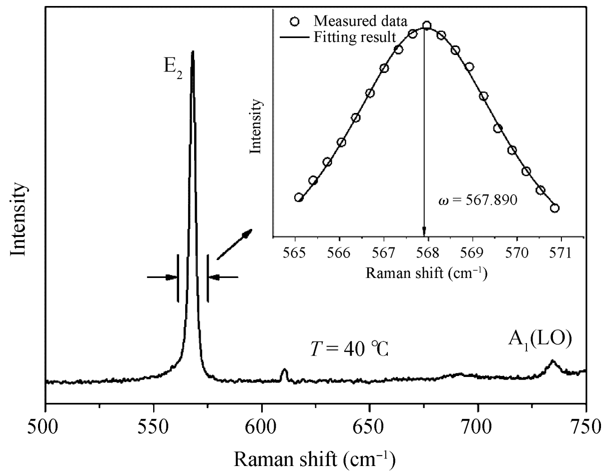

Fig. 2. The measured Raman scattering spectra of the tested AlGaN/GaN HEMT at 40 ℃. The insert is the accurate E2 mode Raman phonon frequency of GaN material obtained by using the Lorentz fitting process.

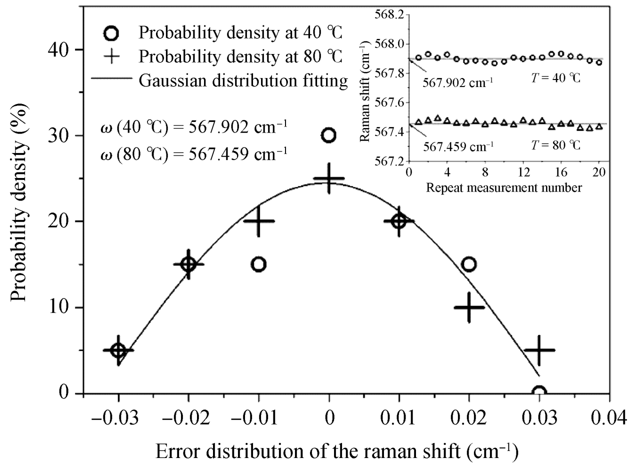

Fig. 3. Random error distribution of E2 mode Raman phonon frequency after the Lorentz fitting process at 40 ℃ and 80 ℃, the insert is the repeat measurement results of E2 mode Raman phonon frequency for GaN material obtained by using the Lorentz fitting process.

The Raman scattering spectrum of the tested AlGaN/GaN HEMT at an ambient temperature of 40 ℃ without electrical power is shown in Fig. 2, the E2 mode Raman phonon frequency (Raman shift, or Raman line position) of the GaN material is selected to be the temperature-sensitive parameter in this work. The spectral resolution of the JYT-64000 micro-Raman system is 0.33 cm^{-1}, which will lead to a temperature uncertainty of ± 15 ℃ and is too coarse for the channel temperature determination for AlGaN/GaN HEMTs. In this paper, we apply the Lorentz fitting method to determine the accurate E2 mode Raman line position according to the measured result. The base function of the Lorentz fitting is shown in Eq. (3).

$$I = I_0 + \frac{2A}{\pi} \frac{B}{4[\omega - \omega(T)]^2 + B^2}, \tag{3}$$

where ω is frequency, I is the measured intensity of the Raman scattering spectra with respect to ω, I_0, A and B are fitting parameters, and $\omega(T)$ is the desired Raman phonon frequency at temperature T. The fitting result of the E2 mode Raman phonon frequency is shown in the insert of Fig. 2, and the accurate E2 mode Raman line position of 567.890 cm^{-1} at 40 ℃ is obtained.

3. Results and discussion

In order to obtain the accuracy of the Raman phonon frequency extracted by this Lorentz fitting method, we applied repeat experiments at ambient temperatures of 40 ℃ and 80 ℃, respectively, without electrical dissipation. The probability density distribution of the random error for the tested Raman phonon frequency is shown in Fig. 3. A stable distribution curve is observed at both 40 ℃ and 80 ℃ with a variance of 0.035 cm^{-1}, which indicates that the random error of the extracted E2 mode Raman phonon frequency by using the Lorentz fitting method is within ± 0.035 cm^{-1} with a confidence probability of 68.3% based on the error theory. According to the –0.011 cm^{-1}/℃ of the temperature coefficient of the E2 mode Raman phonon frequency for GaN material[17], a temperature uncertainty of about ± 3.2 ℃ could be achieved, which is the highest temperature resolution of Raman measurement of GaN material in the published works.

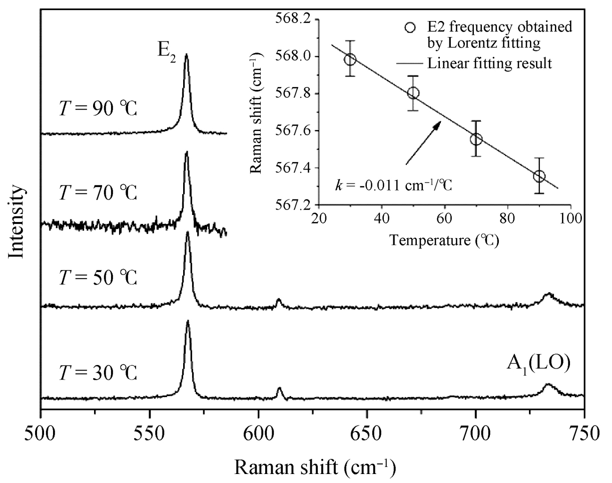

Fig. 4. The Raman spectra of the GaN material in the tested AlGaN/GaN HEMT at 30, 50, 70, and 90 ℃ respectively, the insert is the temperature calibration curve of the E2 mode Raman phonon frequency of the GaN material obtained by using the Lorentz fitting method.

With this observation, the measurement of the channel temperature for AlGaN/GaN HEMTs is investigated by high spectral resolution micro-Raman spectroscopy. Firstly, the temperature dependence of the E2 mode Raman phonon frequency of GaN material is verified by a controllable temperature stage, Linkam TMS94, with an accuracy of ± 1 ℃. Figure 4 shows the Raman shift frequencies of the tested AlGaN/GaN HEMT at different stage temperatures, which vary from 30 to 90 ℃. The corresponding E2 mode Raman phonon frequency is obtained by using the Lorentz fitting method and the calibration curve is shown in the insert of Fig. 4. The temperature coefficient is -0.011 cm^{-1}/℃, which is consistent with the well-acknowledged result published by Liu[17] and also verifies the accuracy of our proposed Lorentz fitting

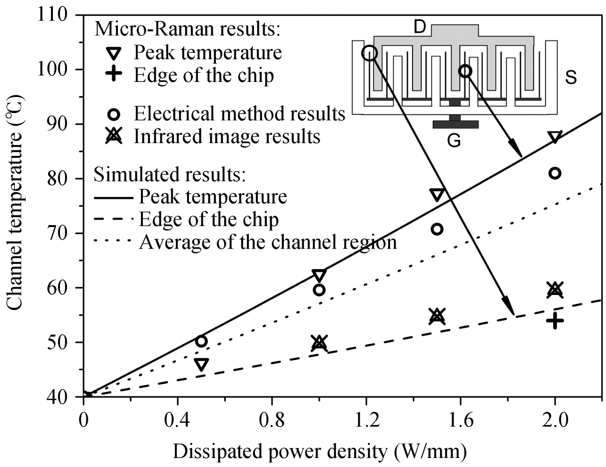

Fig. 5. The experimental and simulated channel temperature with respect to the dissipated power density.

method.

Using the temperature calibration results, the channel temperature and thermal resistance of the AlGaN/GaN HEMTs could be determined. The drain–source voltage (V_{DS}) is fixed to 10 V and the drain–source current (I_{DS}) increases from 50 to 200 mA by adjusting the gate–source voltage (V_{GS}). The stage temperature is fixed to 40 ℃ by a dual-direction semiconductor temperature controller. At the same time, a 3-D numerical thermal simulation is carried out based on FEM tool ANSYS[18]. We consider a heat conduction model with a 1.5-μm-thick GaN layer grown on 400-μm-thick SiC substrate and the Fourier heat conduction equation is solved. The thermal conductivity of GaN and 4H-SiC employed in this simulation is 1.6 W/cm·K and 3.4 W/cm·K, respectively, and the T^{-1} temperature dependence of the thermal conductivity of GaN and SiC material is considered[19]. It is assumed that power is equally dissipated along the width of each gate finger and distributed in a 0.5 μm long region from the edge of the gate contact towards the drain contact[20]. A 40 ℃ constant temperature boundary condition is applied at the bottom of the device. The channel temperature of the tested device is also obtained by using the electrical method with a forward Schottky characteristic as the temperature-sensitive parameter[21] and the infrared image method obtained using an Infrared Micro-Imager RM-50. The testing condition is consistent with the measurement by micro-Raman spectroscopy. Figure 5 displays the measured and simulated channel temperature with respect to the dissipated power density. The channel temperature increases monotonously with the increase of power density, and the maximum channel temperature is observed at the centre of the chip. The channel-to-mount thermal resistance[22] of the tested AlGaN/GaN HEMT by micro-Raman spectroscopy is 22.8 ℃/W. The channel temperature at the edge of the chip is also measured at 2.0 W/mm to verify the simulated results. It could be found that both the simulated peak temperature and the temperature at the edge of active region are in good agreement with the micro-Raman results and support the accuracy of the Lorentz fitting method. However, the thermal resistance tested by using the electrical method is 19.6 ℃/W, which is lower than the micro-Raman results. This is because the channel temperature rise tested by the pulsed electrical method is obtained by the temperature shift of the forward gate–source Schottky voltage, which is determined by the temperature rise distribution of the whole channel region. In other words, the channel temperature tested by the pulsed electrical method is an electrical average value, which is lower than the peak channel temperature. Furthermore, the thermal resistance tested by the infrared method is 9.8 ℃/W, which is a severe underestimation because the channel temperature tested by the infrared image method is the average value within the minimum spatial resolution of the infrared signal, which contains both the channel region and the electrode region drain and source. Therefore, comparing with the pulsed electrical method and infrared image method, micro-Raman spectroscopy presents advantage in exploring the peak temperature for multi-finger AlGaN/GaN HEMTs.

4. Conclusion

In this paper, channel temperature measurements of multi-finger AlGaN/GaN high electron mobility transistors by high resolution micro-Raman spectroscopy are proposed. The temperature dependence of the E2 mode Raman phonon frequency of GaN material is selected to be the temperature-sensitive parameter. By using the Lorentz fitting method, the actual uncertainty of the measurement of the Raman line position is ± 0.035 cm^{-1} when using a JYT-64000 micro-Raman system, corresponding to a temperature uncertainty of ± 3.2 ℃ for GaN material, which is the highest level achieved according to the published works. The tested channel-to-mounting thermal resistance of the AlGaN/GaN HEMT sample is 22.8 ℃/W, which presents reasonably good agreement with the simulated results. Comparing with the pulsed electrical method and the infrared image method, micro-Raman spectroscopy presents an advantage in exploring the peak temperature for AlGaN/GaN HEMTs.

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