Reliability of High-Speed Devices: Probing of Self-Heating with Nanosecond Time-Resolution

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Abstract

We report on the development of time-resolved thermography to measure device temperature with sub-micron spatial resolution and with time resolutions as short as 40 ns. This new technique is demonstrated on AlGaN/GaN electronic devices (transistors and ungated devices). Temperature determination of the devices is based on micro-Raman spectroscopy employing sub-bandgap nanosecond laser pulses. Heating and cooling cycles of AlGaN/GaN devices due to self-heating were measured in the device plane as well as three-dimensionally for different device layouts. We find device layout to affect thermal device time constants.

INTRODUCTION

Radar, communication and computing transistor applications are often dominated by pulsed device operation, with pulse lengths on the order of 10 - 250 µs for radar, sub-microsecond to millisecond for communication and even shorter pulse lengths for computing applications. An excessive transient temperature rise in the operating transistor can lead to catastrophic device failure; elevated temperatures reduce the transistor lifetime and deteriorate their performance. However, there is as yet no direct experimental probing of this transient temperature rise possible, i.e., of the self-heating in high-speed devices due to Joule's heat dissipation. This is since probing temperature with the high speed and the sub-micron spatial resolution required for many of todays' devices is beyond current thermography technologies. For example, electrical characterization can be employed to estimate transient temperatures with high time-resolution if carrier trapping effects can be neglected, but even then it determines only an average device temperature, and is therefore not able to detect the peak temperature in the device hot spots [1]. On the other hand, the commonly employed IR thermography, although providing spatial information on device heating, lacks the sub-micron spatial resolution necessary for many of today's devices. While our recent development of Raman thermography [2,3] has enabled the sub-micron spatial resolution measurement of temperature in semiconductor devices, which is a significant improvement over IR thermography, direct access to the temporal evolution of device temperature has so far not been possible. In this work, we report on the development of a novel nanosecond micro-Raman thermography technique to measure time-resolved the active region temperature in semiconductor devices with sub-micron spatial resolution. This is demonstrated on AlGaN/GaN electronic devices. The developed technique is also suitable for other device systems such as GaAs, InP and Si. We illustrate a temporal and spatial resolution of 40 - 200 ns and 0.5 - 0.7 µm, respectively. The ability to probe for the first time directly transient temperatures in high-speed devices with not only high spatial resolution, but also with high temporal resolution, offers new opportunities to device researchers and designers to optimize device performance and reliability of new as well as traditional device systems.

EXPERIMENTAL DETAILS

AlGaN/GaN heterostructure field effect transistors (HFETs) and ungated devices on 400 µm thick SiC substrates were fabricated. More details on the devices can be found in [2]. Raman spectroscopy was used to determine device temperature when operating the devices using microsecond long electrical pulses. Determination of

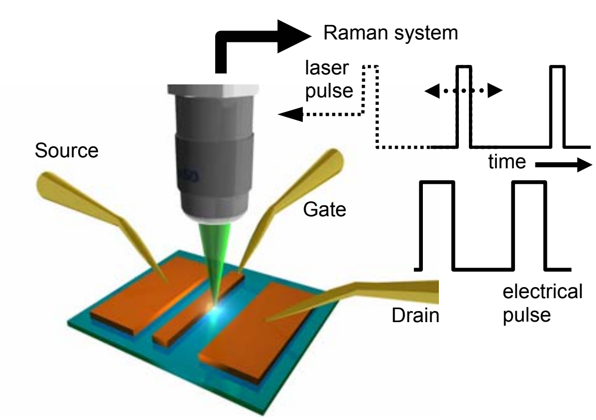

FIGURE 1: Schematic of nanosecond Raman thermography setup.

temperature using Raman spectroscopy is based on the fact that the frequency of phonon modes is temperature dependent. While the established Raman thermography uses a continuous wave (CW) laser to determine temperature of DC operated devices or time-averaged temperature in pulsed devices [2,3], a pulsed laser source was employed here. A schematic of the experimental setup is shown in Figure 1. The Raman signal is only generated for the duration of the laser pulse, impinging on the device at a well defined time-delay after the electrical excitation of the device. Temperature determined in this way corresponds to the device temperature at the chosen time-delay between optical and electrical pulse. The temporal evolution of device temperature is obtained by varying this time-delay. An acousto-optic modulator (AOM) was used here to generate optical pulses of 40 - 200 ns lengths, determining the time resolution of the measurement, while probing up to GHz is possible using pico- and nanosecond pulsed laser sources. Sub-bandgap 488nm and 532nm laser sources were used here for the experiments to avoid any influence of the measurement technique on the device operation, while above bandgap lasers could be used if low laser powers are employed in the measurements. The laser was focused onto a 0.5 - 0.7 µm spot size on the devices, which corresponds to the spatial resolution of the temperature measurement. Further details on the experimental setup can be found in [4].

RESULTS AND DISCUSSION

Figure 2 depicts device temperature recorded in the center of an ungated AlGaN/GaN device operated with 2 µs long electrical pulses and 50% duty cycle. Apparent is a fast temperature rise from about 60 °C to 100 - 120 °C within sub-200ns after switching the device on, followed by a slower temperature rise towards the end of the electrical pulse. A peak temperature of ~140 °C is reached at the end of the electrical pulse. Device lifetime is affected by elevated device temperatures and this device temperature needs to be considered for estimation of device lifetime, in particular, for analysis of accelerated lifetime testing data. We note that thermal equilibrium is never fully reached during the microsecond long electrical pulse duration when operating this device, neither does the device fully cool down to room temperature between the electrical pulses, despite the high thermal conductivity of the SiC substrate. SiC is currently the preferred substrate for AlGaN/GaN transistors due to its high thermal conductivity of 3 - 4 $Wcm^{-1}K^{-1}$, which is one order of magnitude higher than the thermal conductivity of the alternatively used sapphire substrates. The thermal time constant of a device/substrate system scales inversely proportional to its thermal conductivity [4]. If a faster thermal characteristic than possible for devices on SiC substrates is needed, use of even higher thermal conductivity substrates such as diamond could be considered, apart from a resulting further decrease in device temperature. We note that devices grown on sapphire substrates are more than ten times slower thermally than devices on SiC substrates [4]. Figure 2 also shows results from a thermal finite difference simulation. Reasonably good agreement with experiment was achieved.

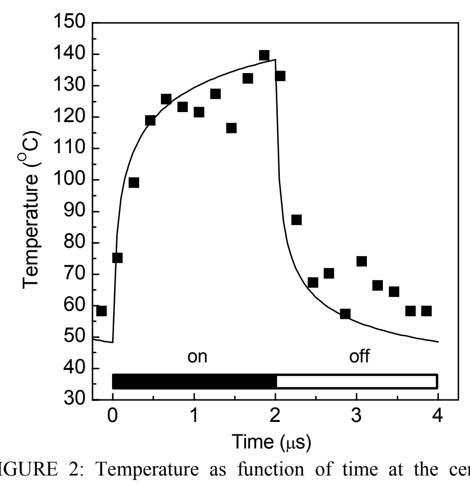

FIGURE 2: Temperature as function of time at the center of an ungated AlGaN/GaN device on a SiC substrate with 5 µm contact separation, grown on a SiC substrate, operated with 2 µs long 20 V (165 mA) square bias pulses and a 50% duty cycle, together with simulation data; device width is 150 µm. Time resolution of the measurement was 200 ns.

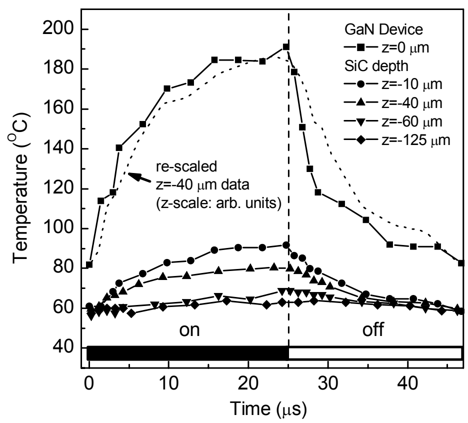

FIGURE 3: Temperature at the center of an ungated AlGaN/GaN device on a SiC substrate with 20 µm contact separation, in the device and at different depths inside the SiC substrate; device width is 150 µm. The device was operated with 25 µs long 40 V (159 mA) square bias pulses and a 50% duty cycle. Note the data recorded 40 µm below the device structure inside the SiC substrate is re-plotted, re-scaled, as dashed line for easy comparison to the time evolution of the device temperature. Time resolution of the measurements was 200 ns.

Figure 3 illustrates the ability of the developed technique to not only probe temperature in a device, but also three dimensionally from a device into the SiC substrate. The results display the temperature evolution in an ungated AlGaN/GaN device and at different depths inside the SiC substrate with the device operated with 25 µs long electrical

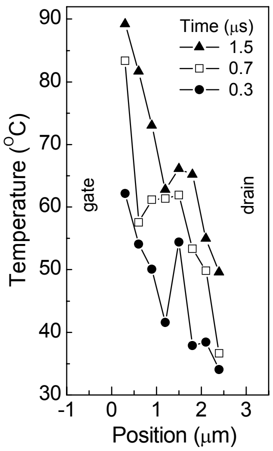

FIGURE 4: Temperature profile as a function of time in the gate-drain opening of an AlGaN/GaN HFET on a SiC substrate (source-drain opening of 7.5 μm, 2 μm long gate), with the device operated with 2 μs long 30 V (58 mA) square drain pulses at zero source-gate bias, 50% duty cycle; device width is 100 μm. Electrical pulses start at t = 0 s. Time resolution of the measurements was 200 ns.

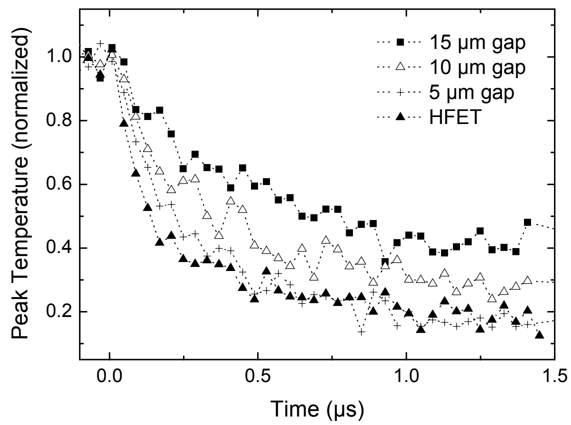

FIGURE 5: Normalized peak temperature as a function of time in ungated AlGaN/GaN devices with different contact separation and in an AlGaN/GaN HFET (source-drain opening of 4 μm, 0.25 μm long gate), all on SiC substrates. Device width of the ungated devices is 150 μm, of the HFET is 125 μm. Electrical input power was chosen for peak temperature to reach ~110 °C for all devices. The devices were switched off a t = 0 μs. Experimental time resolution was 40 ns.

pulses. Temperature decreases into the SiC substrate due to heat diffusion. Temperature tends to rise and fall slower the further inside the SiC substrate it is probed. This is illustrated in Figure 3 where a measurement taken 40 μm below the active device region is re-scaled and compared to the temperature evolution of the device. In particular, a significantly slowed down temperature decrease after switching the device off is apparent. Furthermore visible is a less abrupt temperature decrease in the SiC substrate once the device is switched off, as well as there are indications for a small time delay for when peak temperature is reached if temperature is probed even further inside the SiC substrate. Such thermal behavior has some analogy to a periodically driven capacitive electrical circuit, with modified time responses due to the depositing and removing of heat from the substrate similar to the charging and de-charging of a capacitor.

Figure 4 displays linescans across the gate-drain opening of an AlGaN/GaN HFET taken at different times after switching the electrical pulse on. This result illustrates the lateral spatial resolution achievable with the technique developed here. Peak temperature is located on the drain side of the gate contact. This is expected as this is the device region where the peak electric field is located. The peak temperature increases with time during the electrical pulse duration. The major part of this temperature rise occurs within the first ~0.3 μs after switching the electrical pulse on at t = 0 μs, with a slower rate of temperature increase from 0.7 to 1.5 μs. This is similar to the temporal evolution of the ungated devices shown in Figure 2.

To study differences in thermal time constants between ungated devices and HFETs, as well as the influence of device layout on thermal time constants, the evolution of device peak temperature was recorded in ungated devices with different contact separation, i.e., with different channel length, and of an HFET. Figure 5 displays the measured peak temperature as function of time after switching the devices off. In the ungated devices the electric field, i.e., the heat source in the devices, extends across the whole channel, while for the HFET the heat source is restricted to about 0.5 μm length situated near the drain side of the gate contact [5]. The wider the heat source the less lateral heat diffusion will occur within the device channel due to a smaller lateral temperature gradient, i.e., the slower the thermal behavior of the devices should be. This is apparent in Figure 5. The slowest thermal behavior is evident for the device with 15 μm contact separation, i.e., with a heat source of ~15 μm length. Heat diffusion is dominated here by vertical heat diffusion through the substrate while the relative contribution from lateral heat diffusion is small. As predicted the thermal device time constant decreases when reducing the contact separation to 5 μm, due to increased lateral heat diffusion. We note that the thermal behavior of the ungated device with 5 μm contact separation and of the HFET are similar, although for the initial temperature decay the HFET is somewhat thermally faster than the ungated device as one would expect as this device has the smallest heat generating region of all the investigated devices. Device layout has implications for the thermal time constants of devices, and subsequently also on device temperature when operating devices with an electrical pulse separation on the order of or shorter than their thermal time constant, with subsequent implications for device performance and device reliability.

Conclusions

We developed time-resolved micro-Raman thermography for thermal analysis of semiconductor devices. Spatial resolutions of 0.5 - 0.7 µm and time resolutions as short as 40 ns were demonstrated. Device layout was shown to have implications for thermal time constants of devices. Device thermal time constants decrease the smaller the heat generating region in the devices is. Temperature inside the substrate was demonstrated to follow a slower thermal behavior than the device temperature itself. Although the experimental technique was illustrated here on AlGaN/GaN electronic devices, it is also applicable to other materials and device systems such as GaAs, InP and Si. The results demonstrate the potential of time-resolved micro-Raman thermography for the optimization of performance and reliability of high speed devices and ultimately their improved manufacture.

ACKNOWLEDGEMENTS

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