QUANTITATIVE NANOMETER-SCALE THERMAL METROLOGY USING SCANNING JOULE EXPANSION MICROSCOPY

BY

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THESIS

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ABSTRACT

This thesis presents the development of a quantitative nanometer-scale thermal metrology technique, which is shown to obtain ~10 nm spatial and ~250 mK temperature resolution of the temperature rise of a graphene transistor. This is a large improvement over current state-of-the-art thermal metrology techniques which are on the order of 100 nm spatial and ~200 mK temperature resolution. The atomic force microscope (AFM) based thermal imaging technique is scanning Joule expansion microscopy (SJEM). SJEM operates by supplying a periodic voltage waveform to heat a sample, and the AFM measures the associated thermo-mechanical expansion of the surface. SJEM technique and artifacts are discussed to improve measurement accuracy, and a thermo-mechanical model is developed to correlate surface expansion to sample temperature. To demonstrate the capabilities of SJEM the temperature field of a graphene transistor and its contact to metal electrodes are measured. Thermal images reveal small ~100 nm diameter “hot spots” which exist on the graphene sheet, which are believed to be due to sample fabrication. Comparison of temperature measurements of graphene-metal contacts with a model of heat dissipation in graphene reveal that Joule heating, current crowding, and thermoelectric effects occur at the graphene contact. The agreement of the measurements with predictions demonstrates the high resolution capabilities of SJEM. The development of a quantitative nanometer-scale thermal measurement technique can have significant impacts on material characterization and the microelectronics industry.
This thesis is dedicated to my family and friends for their continued encouragement and support.
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CHAPTER 1: INTRODUCTION

Since its invention in 1986, the atomic force microscope [1] (AFM) has enabled the investigation of materials at nanometer scales. Although numerous techniques have been developed to probe mechanical and electrical properties of materials at these small scales, there currently lacks the ability to obtain nanometer-scale thermal measurements. This has limited researchers from studying heat transport and material properties in nano-scale materials and devices. This thesis describes the development of a quantitative nanometer-scale thermal metrology technique and its implementation to characterize heat flow in graphene transistors.

Current state-of-the-art thermal meteorology techniques can be divided into two categories: optical techniques and scanning probe methods. Optical techniques can obtain quantitative temperature measurements but are diffraction limited to >500 nm resolutions [2]. Scanning probe methods, such as scanning thermal microscopy (SThM), employs a specially fabricated AFM cantilever with either a thermocouple or resistive thermometer at the cantilever tip to measure sample surface temperatures. These probes are capable of obtaining sub-100 nm spatial [2] and ~200 mK temperature resolution [3], but their temperature measurements rely on heat diffusion to the cantilever tip which limits spatial resolution to the size of the tip radius of these probes, ~50 nm. To obtain higher spatial resolutions, this work utilizes an AFM based thermometry technique known as scanning Joule expansion microscopy (SJEM) [4-7]. SJEM operates by supplying a periodic waveform to an electrically conducting sample and monitoring the associated thermomechanical expansion of the sample surface with the AFM. Thus, it has a spatial resolution limited to the radius of a common commercially available AFM cantilever [4],
typically 1-5 nm, and quantitative temperature measurements can be obtained by thermo-
mechanical modeling of the sample [6].

Heating in graphene transistors is measured to demonstrate the resolution of the thermometry technique. Graphene is an atomically-thin single layer of carbon atoms arranged in a hexagon crystal lattice, and is considered the basic building block for carbon materials such as 0D buckeyballs, 1D carbon nanotubes, and 3D graphite. Although graphene was initially isolated in 1975 [8], the electronic properties of the 2D carbon material were not recorded until 2004 [9]. Since then multiple studies have confirmed graphene has exceptional electronic [10] and thermal [11] properties which make it a candidate material for future nanoelectronics [12], transparent displays [13], and chemical sensors [14]. The macroscopic heat dissipation in graphene has been well studied [15]. However, the performance of graphene-based electronics [16] is limited by transport at the contacts between graphene and metal electrodes [17-19] which remain incompletely understood.

This thesis develops an AFM thermal imaging technique which is shown to achieve ~10 nm spatial and ~250 mK resolutions. The implementation and calibration of SJEM is thoroughly discussed, and is utilized to study heat flow in a graphene transistor, specifically focusing on the graphene-metal contacts. Comparison of measurements with simulation allows for the identification of current crowding, Joule heating, and thermoelectric heating and cooling at the graphene contact. The agreement between measured and predicted temperature profiles confirms the AFM thermometry developed in this thesis is able to obtain nanometer-scale temperature measurements.
CHAPTER 2: SCANNING JOULE EXPANSION MICROSCOPY

2.1 Experiment Operation

SJEM is an AFM based imaging technique that can measure temperature distributions with sub-100 nm resolution. Figure 2.1 shows SJEM. An AFM feed-back loop maintains cantilever contact with the surface by monitoring cantilever deflections using a laser-photodiode system and operating a piezoelectric stage. The sample experiences periodic thermo-mechanical expansions due to Joule heating from a periodic voltage or current waveform supplied to the sample. The expansion causes motion of the AFM cantilever tip, which can be detected by a photodiode inside the AFM system. A lock-in amplifier technique is used to record the thermo-mechanical expansion. A back-gate voltage $V_G$ can be supplied to the underlying Si substrate, if it is electrically isolated from the device. It is controlled using a constant voltage source that shares a common ground with the source electrode. The sample is typically covered in a thin polymer film, which acts to amplify the thermomechanical expansion.

![Figure 2.1](image.png)

**Figure 2.1** Experimental schematic for SJEM. Joule heating is induced in an electrically conducting sample by a periodic waveform with amplitude $V_{DS}$. The heating of the sample causes the surface to thermo-mechanically expand at this frequency. The amplitude of this expansion is measured by an AFM cantilever which is in contact with the surface and is recorded using a lock-in amplifier technique.
2.2 Optimization of Scanning Joule Expansion Microscopy

The optimal conditions to create an accurate thermal image with SJEM were found by inspecting the quality of thermal images made with SJEM of the metal constriction shown in figure 2.2. The device shown in figure 2.2 is a gold wire several microns wide patterned on a Si/SiO$_2$ substrate covered in a polymer, similar to the devices featured in reference [6]. The location of the gold wire can be seen using AFM topography as the polymer coating is nearly conformal. The metal narrows into a thin 5 to 2 µm wide wire at a location known as the constriction, where the crowding of current increases Joule heating and the local temperature. The temperature distribution of the microscale heat source as measured by SJEM is qualitatively shown in the figure. Here, yellow represents the hottest area of the image, which is the constriction as expected. At the base of the constriction, the color slowly fades to red and eventually to blue as the local current density and heating decrease.

![Figure 2.2](image)

**Figure 2.2** (left) Schematic of the constriction in the metal microscale heat source used in SJEM imaging. (right) Example of the thermomechanical expansion image, overlaid on surface topography, obtained from a thermal scan of the microscale heat source. Yellow and blue represent the areas of large and small measured expansion.

Table 2.1 illustrates how cantilever stiffness and waveform frequency affect the measured temperature map of the microscale heater shown in figure 2.2. The effect of varying current or voltage is not shown as the power dissipation of the heater is governed through Ohm’s law. At
low frequencies there can be several parasitic effects which are seen in an SJEM image, here the image is distorted by tip-sample interactions or interference with the AFM feedback loop. At about 100 kHz, the soft cantilever is close to its resonant frequency when in contact with the sample surface. Imaging near this frequency can be beneficial as the cantilever dynamics can amplify the surface expansion, similar to DART mode scanning for piezoresponse force microscopy (PFM) [20]. However the resonant frequency is dependent on the local sample geometry and, if the resonance is not tracked, then the result is an amplification of different parts of the image as shown in table 2.1. This occurs again for the soft cantilever at ~200 kHz as the frequency approaches the second contact resonance. Shown in table 2.1 the stiff cantilever is less effected by these artifacts and is able to yield consistent, high quality images for frequencies >50 kHz. To obtain high quality thermal maps it is recommended to avoid contact resonant frequencies and use stiff cantilevers.

Table 2.1 Comparison of thermal images of the microheater from figure 2.2 using a soft (<< 1 N/m) and stiff (>> 1 N/m) cantilever with varying frequencies. The applied waveform is sinusoidal. The soft cantilever has resonances in contact with the surface of ~100 kHz and ~250 kHz. The images are the surface topography overlaid with the thermo-mechanical expansion, with yellow and blue representing large and small expansions.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>≤50 kHz</th>
<th>~100 kHz</th>
<th>~165 kHz</th>
<th>~200 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft Cantilever</td>
<td><img src="image1.png" alt="Image 1" /></td>
<td><img src="image2.png" alt="Image 2" /></td>
<td><img src="image3.png" alt="Image 3" /></td>
<td><img src="image4.png" alt="Image 4" /></td>
</tr>
<tr>
<td>Hard Cantilever</td>
<td><img src="image5.png" alt="Image 5" /></td>
<td><img src="image6.png" alt="Image 6" /></td>
<td><img src="image7.png" alt="Image 7" /></td>
<td><img src="image8.png" alt="Image 8" /></td>
</tr>
</tbody>
</table>
Figure 2.3 compares change in image quality when using either a bipolar or unipolar waveform. As power dissipation scales with the square of the applied voltage, the bipolar waveform heats the sample at both the first and second harmonics [5]. The faster heating rate can significantly limit heat diffusion and sample thermo-mechanical expansion compared to a unipolar waveform applied at the same frequency. For example, the use of a unipolar square wave at 50% duty can increase the thermo-mechanical expansion by ~3 times, when compared to a bipolar sine wave at the same frequency. The increase in signal can be attributed to the increased power dissipation associated with the square wave and the increased time for thermal diffusion. The unipolar waveform is also beneficial for observing thermal phenomenon which are dependent on the direction of the applied electric field. Thus, the combination of unipolar and bipolar waveforms can help to decouple electrical and thermo-mechanical induced sample expansions.

![Figure 2.3 Qualitative thermal images of the microheater of figure 2.2 using a bipolar sine wave (left) and a unipolar square wave at 50% duty (right). Both waveforms have an applied frequency of 250 kHz and were taken using a stiff cantilever. The images are the surface topography overlaid with the thermo-mechanical expansion, with yellow and blue representing large and small expansions.](image)

### 2.3 Thermo-mechanical Model

The measured sample expansion can be related to the temperature rise of the microscale heater through a proportionality constant [6] which is obtained by modeling heat flow within the
sample. Shown in figure 2.4 a one-dimensional simulation predicts heat flow perpendicular to
the sample surface using the transient heat diffusion equation with constant coefficients. The
simulation uses an implicit solution method. The top surface, which is wetted by air, is modeled
as adiabatic and the bottom surface is modeled as a heat sink. The one-dimensional model is
used as samples are much wider than they are thick, and the temperature gradient perpendicular
to the surface is often much larger than the temperature gradient in the plane of the surface. The
simulation input is a sinusoidal heat generation within the device, and the output is the
temperature distribution. The temperature-dependent thermomechanical expansion is then
calculated in the z-direction for each element by taking the product of the element length,
temperature rise, and linear thermal expansion coefficient. By summing the expansion of each
element, the simulation calculates the sample expansion $L$. This processes is repeated for each
time step, $t$. The model runs for 100 heating cycles to ensure it is at steady state. At steady-state
the amplitude of sample expansion and temperature rise of the heating element is found by $\Delta L_{ss} = \max(L_{SS}) - \min(L_{SS})$ and $\Delta T_{ss} = \max(T_{SS}) - \min(T_{SS})$ where the subscript $SS$ denotes time steps
contained in the steady-state period. The ratio of $\Delta T_{ss}$ to $\Delta L_{ss}$ yields the proportionality constant
that relates the measured expansion to heater temperature.

Figure 2.4 is a plot of the predicted temperature distribution of the sample as a function
of time for the steady-state period for the microheater of figure 2.2. The thin gold heating layer is
not modeled in this simulation as it is much thinner than the 1 µm thick layer of polymer on the
surface. As shown in figure 2.4 heat spreads into both the polymer above the microheater and the
underlying silicon substrate. The silicon can contribute a significant amount to the measured
thermo-mechanical expansion and has been shown to be as high as $\sim$50% of the measurement for
$< 100$ nm polymers with applied heating frequencies $< 100$ kHz. As frequency increases the
model predicts the amount of the thermo-mechanical expansion will decreases as heat diffusion from the microheater becomes limited. Thus, the spatial resolution of SJEM can be increased at higher frequencies but the measurable signal will decrease. As shown in the figure, there is a slight delay between the maximum of the applied waveform and the measured maximum surface expansion. This time dependence of the measurement is believed to be related to interfacial contact resistances and the thermal diffusivities of the material. Therefore SJEM may be capable of measuring local thermal properties and interfacial thermal conductances.

Figure 2.4 Thermo-mechanical model of sample expansion due to sinusodial heating. The vertical axis represents the distance perpendicular to the sample surface and the horizontal axis is time. The local temperature rise is represented by the color as shown in the color bar. The polymer on the top surface is modeled 1 µm thick and the image is scaled to include one half a period of the applied waveform. The black and green lines are the applied waveform and the predicted surface expansion. The lag in time between the two waves is dependent on contact resistances and thermal diffusivities.
CHAPTER 3: GRAPHENE TRANSISTORS

3.1 Device Information

Figure 3.1 shows a temperature map of a typical graphene transistor used in this study. Heating is induced by a square wave with 50% duty at amplitude $V_{DS}$ applied to the graphene sheet by the two Pd electrodes contacting the device. The graphene was mechanically exfoliated [15, 21] on 300 nm of thermal SiO$_2$ with highly n-doped Si as the back-gate. Samples were annealed in a chemical vapor deposition chamber with Ar/H$_2$ at 400 °C for 35 min before and after graphene deposition [22]. Electron-beam lithography patterned the electrodes and shaped the graphene sheets. Cr/Pd (0.5/40nm) source and drain electrodes were evaporated on to the sample, followed by an oxygen plasma etch to define the device shape. For thermal AFM measurements, a 65 nm layer of PMMA was spun onto the device.

Figure 3.1 Temperature of a typical graphene transistor overlaid on topography. The device is heated with a square wave, 50% duty, with amplitude $V_{DS}$ at 65 kHz. The applied back gate $V_G = 0$ V is such that the majority carrier in the sheet are holes.
3.2 Thermal Imaging of Graphene Transistors

Figure 3.2 details the temperature rise of a graphene transistor, similar to the device featured in figure 3.1, with a channel length $L = 5 \, \mu m$ and width $W = 4 \, \mu m$, with a spatial resolution of $\sim 10 \, nm$. The graphene sheet is heavily hole doped as the back gate voltage $V_G$ and $V_{DS}$ are smaller than the Dirac voltage $V_0$. There are several small $\sim 100 \, nm$ “hot spots” present in the sheet. The size of the small hot spots is consistent previous observations of carrier puddles which form in graphene on SiO$_2$ [23]. Thus, the high resolution temperature map created of the graphene sheet allows a direct observation of these small regions of carrier depletion. These hotspots were removed in this device by performing a current anneal (passing a large current through the device) and then re-spinning the PMMA coating. This helps to remove the adsorbents trapped between the PMMA-graphene or graphene-SiO$_2$ interface. However, a “hot line” remains present in the heating image. The physics of the localized “hot spot” is still not understood and is a subject of further research.

![Graphene](image)

**Figure 3.2** Temperature map of a graphene transistor of length $L = 5 \, \mu m$ and width $W = 4 \, \mu m$. The multiple $\sim 100 \, nm$ “hot spots” (left) which are removed by changing processing conditions (right). The dashed lines indicate the Pd electrodes. The origin of the “hot line” present in both images is currently unknown.
3.3 Thermal Measurements of Graphene Contacts

Figure 3.3 shows the measured temperature field at the graphene-Pd contact electrodes for two devices with $W = 4$ and 6 $\mu$m and $L = 5$ $\mu$m. Device heating was induced with a 65 kHz, 50% duty, square wave with amplitude $V_{DS} = 1$, 1.5, and 2 V, and $V_G < V_0$ such that the samples are hole doped. To change the direction of hole flow for each bias condition the leads contacting the sample are switched. Each temperature profile shown is an average of 128 line scans that are 3 $\mu$m long and have a spatial resolution of ~10 nm with a temperature resolution of ~250 mK. The temperature resolution is based off a 90% confidence interval for each data point, which on average was <250 mK. In the graphene sheet Joule heating is evident as the measured temperature scales with the square of the applied voltage, consistent with previous observations [15]. To fully understand the temperature field at the graphene-Pd contact for both devices a comparison of the measured results with detailed modeling is necessary and is discussed further in the next section.

Figure 3.3 Measured temperature field at the graphene-Pd contact electrodes for a $W = 4$ (left) and 6 $\mu$m (right) device with $L = 5$ $\mu$m. The black line is the sample topography and the Pd electrode is located at $x = 2.5$ $\mu$m. The blue solid lines indicate the temperature for hole flow into the electrode and the dashed red line corresponds to hole flow out of the contact. Three different bias values are used for $V_{DS}$. 
3.4 Thermal Modeling of Graphene Contacts

Figure 3.4 shows the predicted temperature rise form a finite element model which describes Joule heating (JH), current crowding (CC) and thermoelectric (TE) effects at the contact between the graphene sheet and metal electrode. As shown in the figure, heating in graphene is caused by primarily by JH as JH effects are large in the graphene sheet. However, JH effects do not describe any heating between the graphene and metal contact. Previous studies have shown CC occurs for both graphene [14] and carbon nanotubes [24] into metal contacts. CC introduces an effective current transfer length between the graphene and metal $L_T = (\rho_C/R)^{1/2}$, where, $\rho_C$, is the contact resistivity [25, 26]. This current crowding is similar to the constriction of the metal microscale heater of figure 2.2, and introduces additional resistive heating at the graphene-metal contact increasing the local temperature. The TE effect has also been observed in graphene [27-29] and it is included in the model by the calculation of a Seebeck coefficient at each finite element using the semi-classical Mott relationship [28]. TE heating and cooling at the contacts is calculated by multiplying the local Seebeck coefficient by the element temperature, voltage drop, and device width divided by the contact resistivity. This can be either positive or negative depending on the direction of current flow, which implies either TE induced heating or cooling can occur at the contact. For the model to match published thermopower measurements of graphene [27] the predicted Seebeck coefficient is multiplied by a fitting parameter $f = 0.7$. It is believed that the model over predicts the thermopower of graphene due to sample and substrate defects and impurities.
Figure 3.4 Predicted temperature field at the graphene-Pd electrode for a $W = 4$ with $L = 5 \mu m$ device with $V_{DS} = 1 V$. The vertical dashed line indicates the location of the graphene-Pd interface, similar to figure 3.3. The blue solid lines indicate the temperature rise for hole flow into the electrode and the dashed red line correspond to hole flow out of the contact. The acronyms are JH for Joule heating, CC for current crowding, and TE for thermoelectric.

Figure 3.4 shows how JH, CC, and TE effects change the predicted temperature rise of the graphene-Pd interface. The JH model predicts the temperature rise of the graphene sheet, but the temperature profile quickly drops in the metal electrode, as the electrodes act as a heat sink. The addition of CC introduces an additional heating into the electrode. As shown in figure 3.4, the “JH + CC” model is able to approximate the measured electrode temperature, figure 3.3, but is unable to predict the change in temperature with current flow direction. The TE effect is able to account for the transport of thermal energy with charge and its inclusion into the “JH + CC” model predicts the change in temperature with carrier flow direction. The TE effect changes the temperature at the contact by $\sim 0.5 K$, dependent on the direction of carrier flow, which is $\sim 30\%$ of the predicted temperature rise of CC and JH effects. As discussed below all three effects are needed to match the measurements made in figure 3.3.
Figure 3.5 (a,b) Measured and (c,d) predicted temperature profiles at the graphene-metal electrode for a $W = 4$ (a,c) and 6 $\mu$m (b,d) device with $L = 5$ $\mu$m. The black line (a,b) is the sample topography and the Pd electrode is located at $x = 2.5$ $\mu$m. This is indicated by the vertical dashed line in (c,d). The blue solid lines indicate the temperature rise for hole flow into the electrode and the dashed red line corresponds to hole flow out of the contact. Three different bias values are used for $V_{DS}$. The inset (c,d) shows the graphene resistance $R_S$ vs. gate voltage $V_G$ for both experiment (dots) and simulation (solid black line).

Figure 3.5 compares the measured temperature profiles with simulation predictions. All three heating components JH, CC, and TE are required to match the measured temperature profiles. The simulation requires only three fitting parameters to match temperature measurements. The three fitting parameters are the device mobility $\mu$, carrier puddle density $n_0$, and graphene-Pd contact resistivity $\rho_C$. The mobility and contact resistivity are obtained by matching the electrical measurements to predictions in the insets of figure 3.5. However, the two
point measurements also include the resistance due to the Pd lines \( R_{\text{Series}} \). Accounting for this series resistance with the graphene sheet allows for accurate estimation of the device mobility. \( R_{\text{Series}} \) was found to equal 650 \( \Omega \) and 575 \( \Omega \) for the \( W = 4 \) and 6 \( \mu \)m wide devices, which gave the best-fit mobility discussed below. This corresponds to a Pd resistivity \( \rho_{\text{pd}} = 17 \mu \Omega \cdot \text{cm} \) for the Pd electrodes used in this study. The best-fit mobility and carrier puddle density was then found to be \( \mu = 3230 \text{ cm}^2/\text{V} \cdot \text{s} \) and \( n_0 = 1.8 \times 10^{11} \text{ cm}^{-2} \) for the 4 \( \mu \)m wide device, and \( \mu = 4000 \text{ cm}^2/\text{V} \cdot \text{s} \) and \( n_0 = 1.2 \times 10^{11} \text{ cm}^{-2} \) for the 6 \( \mu \)m wide device, consistent with previous studies [15, 23, 30]. The graphene-Pd contact resistivity \( \rho_{\text{C}} \) was found by fitting the predicted and measured temperature profiles in figure 3.5. The best-fit contact resistivity was found to be \( \rho_{\text{C}} = 150 \) and 200 \( \Omega \cdot \mu \text{m}^2 \) for the \( W = 4 \) and 6 \( \mu \)m devices. Once \( \mu, n_0, \) and \( \rho_{\text{C}} \) are known the temperature profile of the graphene sheet can be found for each applied bias. The agreement of the predictions to measurements for each bias and current flow direction confirms that current crowding and thermoelectric effects are present at metal-graphene contacts. This also demonstrates that SJEM is capable of nanometer-scale temperature measurements.
CHAPTER 4: CONCLUSIONS

4.1 Applications

The development of a quantitative nanometer-scale thermal metrology technique has potential impact on the nanoelectronic industry and as a tool for nano-scale material characterization. The non-invasive nature of the measurement enables imagining of buried heat sources, which is similar to many commercial electronic devices which have multiple insulators and metal vias layered upon each other. The ability to directly measure local hotspots in electronic devices can help engineers redesign electronics to reduce localized heating. Non-invasive measurements are also useful when measuring materials which are unstable in ambient conditions as the sample can be encased in a protective coating. However, the largest application for this technology may be in research labs equipped with an AFM. Current state-of-the-art thermal metrology techniques with sub-100 nm resolution require both an AFM and specially fabricated cantilevers. These cantilevers typically have low yield and their measurements require are primarily qualitative. As SJEM requires a lock-in amplifier and standard AFM cantilever, many AFM labs are currently equipped to make accurate nanometer-scale temperature measurements. Thus, the largest impact of the techniques discussed in this thesis is in the development of an easily implemented research tool to study of nanometer-scale thermal phenomenon.

4.2 Future work

Future work will focus on enhancing SJEM resolution from ~10 nm spatial and ~250 mK temperature resolution, shown in the current work, to fundamental limits. This will require the creation of a three-dimensional model of heat generation and heat spreading from a nanoscale-size resistive heater into a substrate composed of multiple materials. The simulation will be
coupled to a mechanical model of an AFM cantilever subjected to these surface vibrations. The additional mechanical model will increase the accuracy of the simulation as this enables a direct comparison of the predicted cantilever deflection to AFM measurements. SJEM will also be performed on several custom fabricated circuits to calibrate the model. The fabricated circuits will resemble common structures built in the nanoelectronics industry, so this research can directly increase the current knowledge of nanometer-scale temperature rises and power dissipation in nanoelectronics. These are known to be crucial for both electronic device performance [31] and lifetime [32]. Thus, SJEM research can directly impact the performance and design of nanoelectronics by coupling simulations with experiments to create ultra-high resolution temperature measurements.

SJEM can also be developed to measure the thermal diffusivity of materials with high resolution. SJEM depends on the periodic diffusion of heat through materials. Therefore, by measuring the time-dependent thermo-mechanical expansion and comparing with the developed models, the thermal diffusivity of a material can be extracted. Fabricated samples will need to isolate heat flow from the heater structure into the material of interest. When measurements are coupled with detailed modeling of the fabricated structure, SJEM can be used to create a nanometer-scale map of the thermal diffusivity of a material.

4.3 Summary

A quantitative nanometer-scale thermal metrology technique is developed in this work. SJEM [4-7] improves upon the spatial resolution of both SThM and optical techniques and, when coupled with thermo-mechanical models, can obtain quantitative temperature measurements [6]. Several of the parameters used to create an accurate temperature map are considered in this thesis. It is found that using a stiff cantilever at a frequency where no resonance or surface
interactions occur can yield high resolution images. To verify the resolution of the thermal measurements graphene transistors were utilized as a case study. Preliminary studies of graphene revealed small “hot spots” developed on the graphene sheet, which are likely due to sample processing conditions. When examining the temperature field at a graphene-metal contact the measurements and simulations revealed JH, CC, and TE effects occurred at the interface. The agreement between the measurements and predictions confirms that SJEM is capable of quantitatively measuring nanometer-scale temperature fields.
REFERENCES


