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Nanoscale thermal probing

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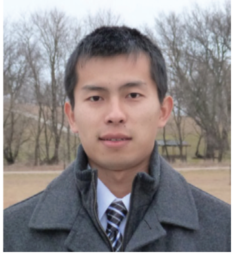
Abstract

Nanoscale novel devices have raised the demand for nanoscale thermal characterization that is critical for evaluating the device performance and durability. Achieving nanoscale spatial resolution and high accuracy in temperature measurement is very challenging due to the limitation of measurement pathways. In this review, we discuss four methodologies currently developed in nanoscale surface imaging and temperature measurement. To overcome the restriction of the conventional methods, the scanning thermal microscopy technique is widely used. From the perspective of measuring target, the optical feature size method can be applied by using either Raman or fluorescence thermometry. The near-field optical method that measures nanoscale temperature by focusing the optical field to a nano-sized region provides a non-contact and non-destructive way for nanoscale thermal probing. Although the resistance thermometry based on nano-sized thermal sensors is possible for nanoscale thermal probing, significant effort is still needed to reduce the size of the current sensors by using advanced fabrication techniques. At the same time, the development of nanoscale imaging techniques, such as fluorescence imaging, provides a great potential solution to resolve the nanoscale thermal probing problem.

Keywords: *nanoscale*; *scanning thermal microscopy*; *feature size*; *near-field*; *Raman spectroscopy*; *near-field*; *resistance thermometry*



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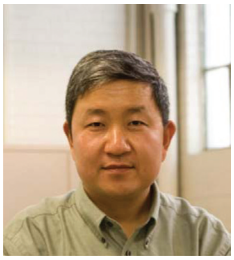

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Along the development of nanotechnology and the tendency of miniaturization in semiconductor industry, a large number of novel devices at the nanoscale have emerged (1). At the same time, heat dissipation in these devices has become a critical problem that limits their broad applications (2). When the device dimension is reduced to be comparable to the mean free path of energy carriers, certain pathways for the heat dissipation are less efficient (3). The accumulation of heat would lead to shorter lifetime of devices or even electrical/mechanical failure (4). Consequently, a better understanding of the thermal performance of nanodevices, especially accurate measurement of local temperature at the nanoscale is extremely important (1). In the past twenty years, extensive study has been focused on this area, in the aim of improving spatial and temporal resolution of temperature measurement (3).

The conventional temperature measurement is either based on the electrical or optical physical properties of materials. For example, the broadly used temperature probe-thermocouple employs the Seebeck effect of thermal electric materials to measure temperature based on

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the thermal equilibrium established at the mechanical contact point (5). The infrared thermometer measures the emission of light at infrared wavelength to extract temperature based on the difference in emission of sample at different temperatures. These methods have played important roles in thermal characterization, being capable of measuring temperature with high accuracy and resolution to a few microns. However, when the development of semiconductor industry requires higher spatial resolution, say sub-micron or even tens of nanometers, these conventional methods would not be applicable due to either the dimension limit of the thermal probe or the diffraction limit of excitation source.

Nanoscale temperature measurement refers to the measurement with dimensions ranging from 1 nm to 100 nm. It is not difficult to understand how challenging this task is to fabricate a thermal probe with such low dimension, especially due to more complicated physical phenomena due to the size effect and ballistic thermal transport. However, as mentioned above, achieving nanoscale temperature probing has practical significance since the accurate temperature information is important for understanding the local thermal response of heating effect at the nanoscale, and meanwhile, has great potential of applications in various fields. For instance, in semiconductor field, the resolution of integrated circuit (IC) has broken through the dimension of 50 nm (4, 6). Their thermal performance needs to be acquired for stable operation under various conditions (4). In bioscience field, thermal imaging of tissue or a single molecule is important for thermal therapies to cure cancer (7). Meanwhile, in the application of materials field, nanoscale temperature probing is used in thermal characterization of nanostructured materials. There is growing interest of nanomaterials, for example, nanowires and nanofilms, for their thermal performance. Nanoscale temperature probing is a good supplement of detecting the hot spot and predicting the thermal performance of these materials (1). In addition, nanoscale thermal mapping is critical for studying thermal response of laser heating effect with nanoscale dimensions, like near-field effect with feature size less than 100 nm (8, 9). The achievement of nanoscale thermal characterization could help with the fast advance in microscopy and manufacturing fields (8, 10).

The demand for nanoscale thermal characterization greatly stimulates the development of measurement techniques. The barrier to temperature measurement with nanoscale resolution can be broken in different ways. The principle approach is to fabricate a nanoscale thermal probe or through a certain medium to achieve thermal probing down to the nanoscale, for example, to invent a nano-thermocouple, or to use an optical method by focusing a light spot to a few nanometers. The other way to achieving nanoscale temperature probing is to measure samples with nano-size. It does not require the measuring probe to feature high resolution but needs the unique feature from the nano-sized sample to be detected and thus makes its temperature distinguishable.

The development of microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS) makes it possible for fabricating temperature sensors with sub-micron size. By attaching it to the tip of atomic force microscope (AFM), the thermal probe is capable of doing nanoscale temperature mapping, which is called the scanning thermal microscopy (SThM). The emergence of nanoparticles with unique optical characteristics provides the opportunity of using the feature size method to realize nanoscale thermal imaging. The near-field effect that successfully overcomes the diffraction limit and accumulates the optical field into the nano-sized region has been applied in temperature probing. In the following sections, a comprehensive review about these nanoscale temperature measurement techniques and their applications is presented, with the aim of constructing a good picture of this field to our best knowledge.

1. Scanning thermal microscopy

The idea of designing devices for nanoscale temperature probing is obvious: one should first see or find the nano-sized target, then realize temperature probing. The development of scanning tunneling microscope (STM) enables surface mapping at the atomistic scale (11), meanwhile provides a great potential to be used in temperature mapping (12). Since the tip can be finely controlled by the piezoelectric actuator to move to less than 1 nanometer close to the sample surface, monitoring the surface temperature by using the tip is practical. In this background, the scanning thermal microscope (SThM) was developed by attaching a temperature sensor on the apex of the tiny tip to realize nanoscale temperature measurement (13).

Its development had experienced stages from the use of STM to the use of AFM as the platform (13). The STM-based measurement requires precise control of the gap between sample and tip because the heat transfer between them is critical to the success of temperature measurement. Tiny variation in the gap would change the thermal resistance and thus affect measurement results a lot. To solve this problem, a feedback control system is used, but this affiliation increases the complexity of the system. Another limitation is that STM could only be applied on metallic samples. If other materials like semiconductors are of interest, AFM is employed to replace STM, not only because of its broader applications, but also more convenient operation to maintain the constant gap between the tip and sample (14).

In AFM-based SThM (Fig. 1), the tip is mounted on a cantilever whose position can be monitored by the

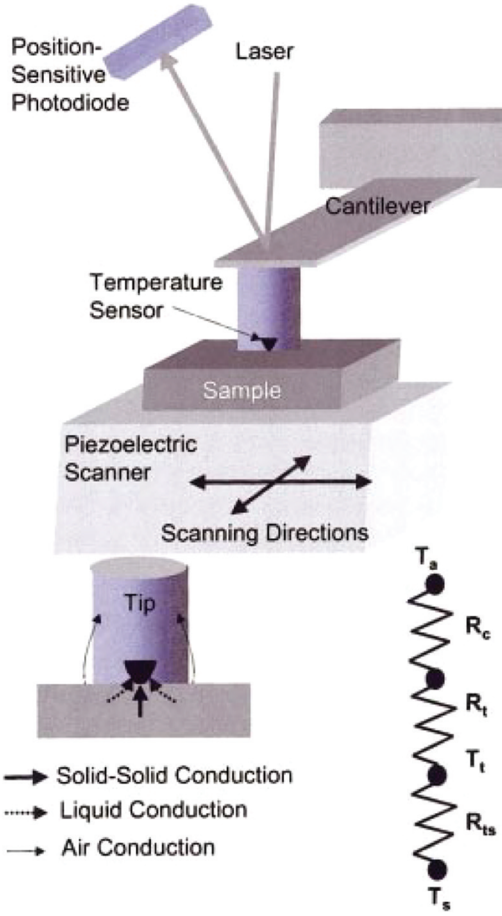

Fig. 1. Schematic of the scanning thermal microscope (SThM) based on AFM, the temperature sensor is attached at the apex of the tip. Reproduced with permission from Reference (1). American Institute of Physics, Copyright (2003).

reflection of a CW laser (1). The atomic force between the sample and tip can be sensed and is kept constant when the setup is used for temperature mapping. The temperature is probed by the sensor fixed at the apex of the tip, and the surface temperature of sample can be obtained by studying the localized heat transfer. The thermal transport between the tip and sample is complicated and tremendous work has been dedicated to study it (15–19). The thermal resistance is mainly contributed by two sources: the solid-solid conduction and air conduction, while the thermal radiation effect is ignored due to the small contribution compared with the above two. In addition, to reduce the uncertainty in defining solid-solid thermal resistance due to roughness, a liquid film is often used at the tip apex to make the heat transfer at the apex more efficient (18, 20). More details about the mechanism of heat transfer between tip and sample can be found in refs. (18, 21, 22).

Various temperature sensors based on different physical fundamentals can be used. A typical one is based on the thermal voltage technique (14), which is called the thermocouple-based sensing method. When the tip scans across the sample surface, the heat transfer between the tip and sample would change the apex temperature of the tip, which can be sensed by this miniaturized thermocouple in the form of voltage difference at the other ends. In the SThM technique, other thermal probes based on the effect of temperature dependence of electrical resistance (23), the contact potential (24), and the thermal expansion effect (25) have been developed. A comprehensive review about these temperature probing methods has been presented in ref. (13).

The SThM technique has been developed for more than 20 years and widely applied in different areas for temperature mapping (23, 26–28) and thermal properties measurement (29–31). The main challenge for accurate measurement is the uncertainty of the heat conduction between the tip and substrate due to the rough surface. In 2008, Wischnath et al. (32) reported a near-field SThM operating in ultrahigh vacuum to detect the thermal current by the radiation effect. The excellence of this design is the elimination of conduction effect of the solid-solid interface or the film between tip and sample by operating the system in a vacuum environment. Meanwhile, this design is capable of thermal imaging for various distance between the tip and sample ranging from 1 nm to around 10 nm with a resolution a few nanometers (32). The restriction of the higher spatial resolution in SThM measurement mainly comes from the fabrication of temperature sensor and tip with stable properties (20, 21). The emergence of photolithography technique provides the solution, which greatly improves the spatial resolution of SThM to less than 50 nm (28). The SThM technique based on the thermal expansion effect features the highest spatial resolution with 10 nm, but an external heating source is needed (33). It is expected that a higher resolution could be achieved as a smaller tip and temperature sensor become available with the development of nanofabrication techniques. The SThM technique has realized high accuracy in temperature measurement with an uncertainty about 10^{-3} K and its temporal resolution is shorter than 1 ms, which is limited by the lock-in bandwidth or the response time of thermal probes (13).

2. Optical feature size method

The optical method is an important option for temperature measurement, and has been broadly applied in research and industry field due to its non-contact and non-destructive probing features. Some techniques are based on the characteristic of materials that the change of temperature will result in the change of optical properties, like emissivity and reflectivity. The temperature can be measured by focusing the light to the interested region and monitoring the change of the light reflection. Several techniques have been developed based on this principle, including infrared thermography and thermoreflectance method. The spatial resolution depends on the size of the focal spot. Extensive research has been devoted to the improvement of accuracy and resolution of these optical thermometry techniques. However, the size of focal spot is not unlimited small due to the diffraction limit. It is dependent on the wavelength of excitation light and the convergence angle which is determined by the numerical aperture of the objective lens. Therefore, it is difficult for these conventional optical probing methods to achieve a resolution down to deep sub-micron.

From another perspective, nanoscale temperature probing can be realized by detecting the temperature of nano-sized samples, for example, nanoparticles. There are some other optical thermal probing techniques which are based on the temperature dependence of electronic and lattice band structure of materials, for example, the fluorescence method and Raman thermometry. The temperature is evaluated by studying the spectrum of emitted photons from the material. Therefore, the resolution will not be limited by the diffraction limit, but by the size of the target under measurement. The temperature can be probed if the signal emitted from the material can be captured. At the same time, the nano-sized measuring target can be used as a thermal probe in nanoscale temperature measurement.

2.1. Nanoscale fluorescence thermometry

As a non-contact and non-destructive method, fluorescent thermometry has been used in numerous thermal imaging applications during the last decade, ranging from MEMS devices (e.g. microelectronic circuits) to single living cell (6, 34). The temperature is determined by analyzing the temperature-dependent fluorescence signal: when the temperature increases, the intensity of excited fluorescence decreases and the peak shifts to longer wavelength (35). Therefore, the phosphor exciting fluorescence signal can act as temperature sensor, and its size determines the spatial resolution of temperature measurement. The work by Li et al. (36) described the temperature measurement technique by using the wavelength shift of individual CdSe quantum dots with nominal diameter of 7–12 nm. Similar work has been done by Bastida et al. (37) in the fabrication of temperature sensors by using two types of quantum dots with 4 nm and 5 nm. Fig. 2 shows the relationship between temperature and fluorescence signal of single quantum dots (36). It is obvious that the fluorescence peak decreases and shifts to longer wavelength while the peak width broadens as temperature goes up. The temperature can be readily determined from linear relationship between temperature and wavelength, intensity and peak width.

Besides quantum dots, various materials can be used as the temperature sensor in the fluorescence method, such as inorganic phosphors, organic dyes, and other nanoparticles (34, 38–40). The selection priority is the material exhibiting high stable fluorescence intensity with no or little influence from the environment. In Löw et al.'s (41) work, the molecular dye Rhodamine B with strong temperature dependence of fluorescence was used for temperature mapping with a spatial resolution less than 500 nm. The excellence of this work is that it successfully minimizes the error induced by the photobleaching effect by using a computer-controlled shutter. It is because that the photobleaching effect would lead to decay of fluorescence intensity, which induces the error in temperature determination. Super-high spatial resolution for fluorescence imaging is achieved by Zhuang's group by using the special patterned illumination, and a detailed review about her work can be found in ref. (42). Their excellent design effectively overcomes the diffraction limit, realized 3D imaging, and could reach a spatial resolution down to 10 nm. One typical technique called

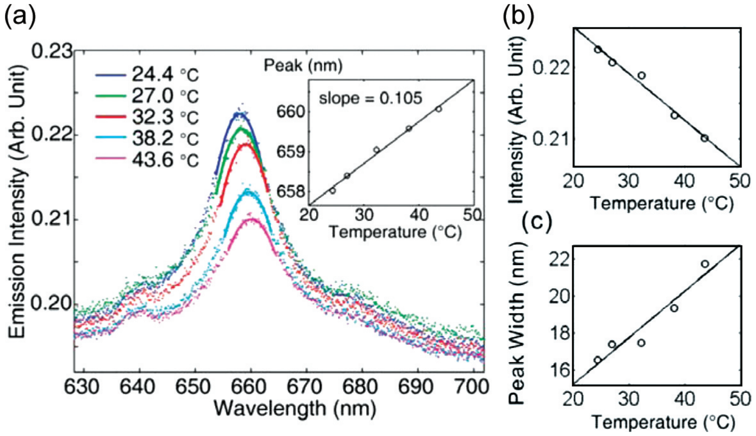

Fig. 2. (a) Spectrum of a single CdSe quantum dots at different temperatures, a slope of 0.105 nm/K is obtained for the relationship between wavelength and temperature; (b) Temperature dependence of fluorescence intensity; (c) Temperature dependence of fluorescence peak width. Reproduced with permission from Reference (36). American Chemical Society, Copyright (2007).

stochastic optical reconstruction microscopy (STORM) realizes a high resolution down to 20 nm by controlling the fluorescence emission from a single molecule (43). Extended application of this technique is expected for thermal imaging with a resolution down to single molecule size. In the fluorescence method, the time response of temperature measurement depends on the quantum efficiency of the measuring target, and the temperature resolution is better than 0.01 K (44).

2.2. Nanoscale Raman thermometry

As another optical method, Raman thermometry has broad applications in characterization of semiconductor materials (45, 46). The Raman signal is an inelastic scattering effect measuring the lattice vibration of the material with the interaction of incident photons. The temperature difference would lead to the difference in lattice vibration, thus, affects Raman signal in the form of intensity, frequency (Raman shift) and width of peaks. When the temperature increases, the Stokes signal (has lower frequency than the incident light) decreases while the anti-Stokes signal (has higher frequency than the incident light) increases. Simultaneously, the Raman peak shifts to the lower wavenumber and peak width broadens. These features provide the opportunity for the Raman spectrum to be used in temperature measurement in a non-contact and non-destructive manner.

In recent years, Raman thermometry has been broadly applied to temperature mapping and thermophysical property measurement of different materials, such as silicon, GaN and carbon nanotubes (CNTs) (45, 47, 48). The resolution of micro-Raman thermometry is generally limited by the spot size of the probing laser. To apply it in nanoscale temperature measurement, as the same principle of the fluorescence method, a sample of nano-size would be employed, if only the excited Raman signal from the sample can be detected. Various nanomaterials whose role is similar to that of phosphor in fluorescence method can be used to apply Raman thermometry. For example, the single-walled carbon nanotubes (SWCNTs) with a feature size less than 100 nm can be used as nanoscale thermal sensor. Fig. 3 shows the temperature dependence of Raman shift of SWCNT rings, different slopes for the temperature dependence of various peaks were observed (49). Other nanomaterials, like silicon nanowires (50) and graphene (51) – a promising material in the semiconductor industry with single layer thickness of carbon atoms, can be used as nanoscale temperature sensors due to their temperature dependence of Raman signal.

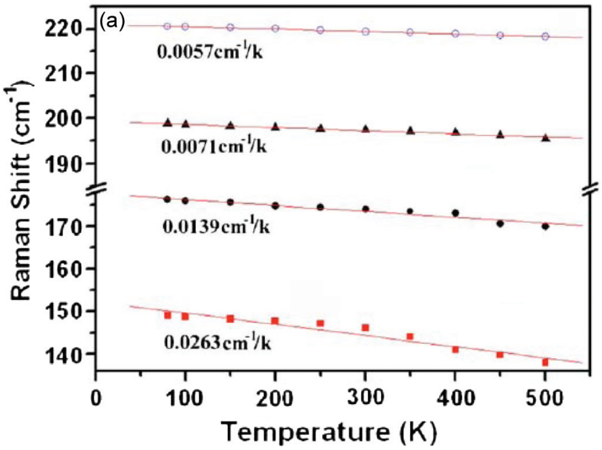

Fig. 3. The linear relationship between temperature and Raman shift of various peaks of SWCNT ring. Reproduced with permission from Reference (49). American Institute of Physics, Copyright (2008).

A recent work by Yue et al. (52) has achieved nanoscale temperature probing of graphene in the thickness direction by using Raman thermometry (Fig. 4). An epitaxial graphene layer grown on 4H-SiC was applied with steady-state joule heating. Simultaneous Raman measurement was conducted by focusing the probing laser on the graphene layer. From the Raman spectrum, the temperatures of graphene and SiC were measured and distinguished, and the interfacial thermal resistance between graphene and SiC was obtained from their temperature differential. Fig. 4b shows how the Raman frequency varies against temperature for SiC and graphene. This calibration result is used in temperature measurement of graphene and SiC by studying the shift of their Raman frequency under joule heating. In this work, the epitaxial graphene has three layers (1 nm thickness) and the penetrating depth of laser in SiC is tens of microns. Therefore, the spatial resolution for temperature probing in this experiment achieved 1 nm and a few microns on the graphene and SiC side, respectively. It is expected the spatial resolution can be improved down to sub-1 nm scale when a single-layer graphene is used. Raman thermometry based on nanoscale dimension of the probing target could be a very promising direction for future development of nanoscale temperature measurement.

2.3. Combined application with AFM

One limitation of applying the feature size method is the difficulty to precisely control and localize the nano-sized target. For broader applications, it can be combined with an AFM, which can provide the tip as a carrier of these optical thermal sensors or directly as the temperature sensor if the tip can excite the Raman or fluorescence signal. Similar to the mechanism of the SThM technique, the temperature of sample surface can be probed by detecting the optical signal from the sensor. This method can be classified as a subset of SThM techniques, or extended application of the feature size method.

In Aigouy et al.'s (6) work, they used erbium/ytterbium co-doped fluoride glass as a fluorescent particle to glue it at the end of an AFM tip. The temperature is determined by the ratio of two peaks in the fluorescent spectrum.

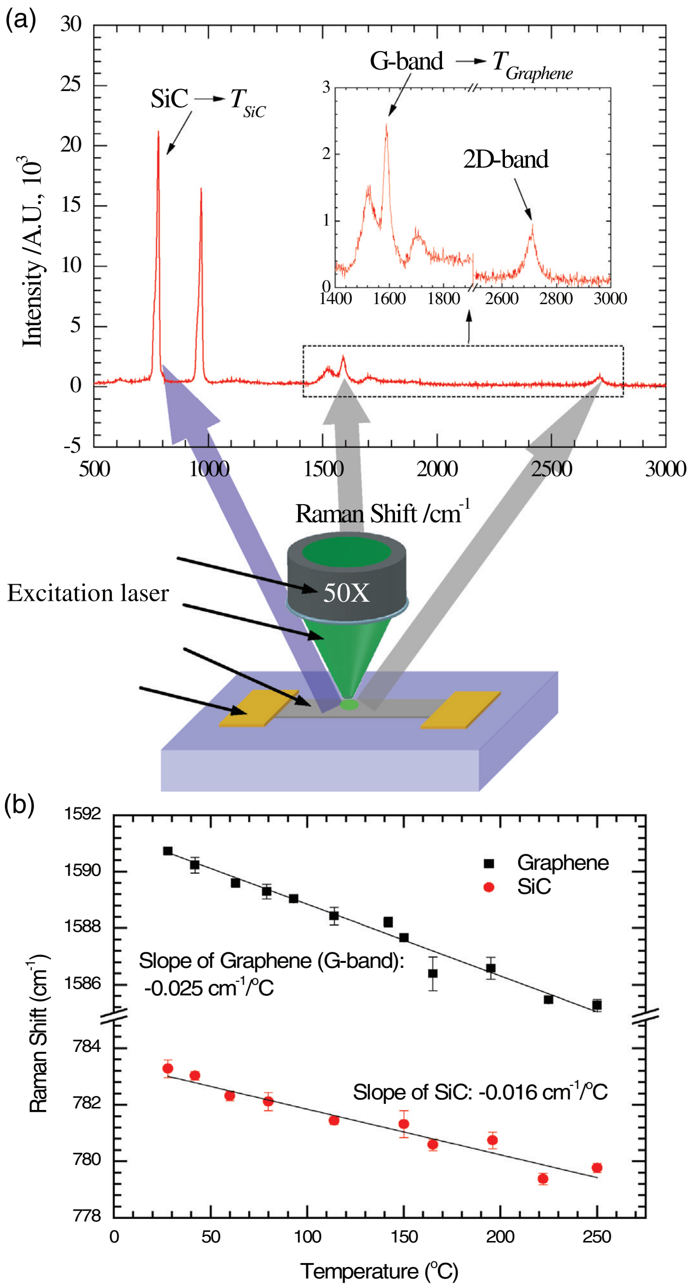

Fig. 4. (a) Schematic of micro/nanoscale spatial resolution temperature probing for interfacial thermal characterization between epitaxial graphene and 4H-SiC; (b) Calibration result of temperature dependence of Raman shift. Reproduced with permission from Reference (52). John Wiley and Sons, Copyright (2011).

A successful application of their method is the temperature mapping on a metal-oxide-semiconductor IC. The probing resolution is highly dependent on the size of the particle, which is 1 μm in Aigouy et al.'s work. However, the application of using particle with a size smaller than 100 nm would be possible. In that case, the spatial resolution of temperature measurement would be greatly improved. Similarly, future applications include attaching Raman active nanomaterials, for example, CNTs or graphene flakes, on the AFM tip to resolve nanoscale temperature mapping is expected.

3. Near-field optical temperature measurement

Besides the feature size method, the other method to break the diffraction-limit barrier is to place the excitation source or detection probe close to the sample surface with a distance less than the wavelength. This is named as near-field scanning optical microscopy (NSOM), which has the capacity to deal with the phenomenon smaller than 100 nm by the interaction of electromagnetic waves with objects (53). NSOM can be operated in two modes: aperture and apertureless. The aperture can be used to confine the light source to excite the surface. A high spatial resolution around 25 nm for surface imaging has been achieved by approaching the detector to the object with a very narrow aperture (54). Unlike the far-field which is at least two times wavelength size, this near-field has a strong inductive effect from the currents and charges in the antenna (the geometry to induce the near-field effect), which causes enhancement effect of the optical field. The enhanced optical field existing in a region with only a few nanometers can be used for nanoscale temperature probing. Using near-filed temperature measurement, a response time shorter than 10 μs and high temperature resolution with 0.1 K can be achieved, depending on the signal-to-noise ratio of the optical signal (5).

3.1. Tip induced apertureless NSOM

The tip of AFM is an ideal tool to produce the near-field enhancement effect. An external laser is used to irradiate the side of the tip. An enhanced optical field will appear in a small region beneath it. When the tip is operated in the tapping mode, this setup becomes apertureless NSOM. The enhanced optical field induced by the tip is a consequence of plasmon resonances, which can be used in surface imaging and thermal probing. An extremely high spatial resolution has been achieved at the level of 10 nm, and the resolution (size of optical field) depends on the geometry (size and convergence angle) of the tip (55). The strong optical field leads to intensive photon interaction in the material, and then excites strong inelastic Raman signal and fluorescence, from which the localized temperature can be determined.

It has been demonstrated that the enhanced optical field will generate intensive heating in a nano-sized region, especially when the substrate is in contact with the tip. Using the Raman thermometry method, Yue et al. (9) studied the temperature rise in a silicon substrate under near-field laser heating. In their experiment (Fig. 5), an external continuous laser was adjusted to irradiate the contact region between the tip and sample. A strong optical field appears at the apex of the tip and intensive heating was generated at the subsurface of the substrate. The enhanced Raman signal from this region was captured for temperature determination. Based on the temperature dependence of Raman shift and peak analysis from Raman signal (left in Fig. 5), the localized temperature was probed with a spatial resolution down to sub-10 nm.

3.2. Nanoparticle induced apertureless NSOM

Another commonly used geometry to produce near-field enhancement is nanoparticle, the scale of which ranges from 10 nm to 1 um. In near-field optics, the particle acts as an objective lens to focus the excitation light to a small region. Kühn et al. (56) employed a gold nanoparticle to investigate the near-field enhancement of the fluorescence signal from single molecules. Prior to this study, Emory et al. (57) captured the surface enhanced Raman signal by using a silver nanoparticle attached on a tip. Another study in their group pushed the measurement resolution to a single molecule (58). As an example, Fig. 6a shows the setup of the near-field enhancement induced by a silver particle, and how the enhanced Raman signal was measured (Fig. 6b). Temperature probing could be done and the temperature can be readily extracted from the peaks in the spectrum by studying either the Raman shift or peaks' width. Another example about nanoparticle induced near-field experiment conducted by Baffou et al. (59) successfully realized temperature mapping with 300 nm spatial resolution and accuracy of 0.1°C by using fluorescence thermometry. Theoretically, the spatial resolution in temperature measurement based on nanoparticle induced NSOM can be improved to be less than 100 nm, which is mainly determined by the size of nanoparticles.

3.3. Nanoscale temperature probing based on aperture NSOM

Besides the apertureless NSOM, the NSOM with aperture probes could also be used in nanoscale temperature probing. The confined light source by the nano-sized aperture can induce Raman or fluorescence signal. With the aim of high spatial resolution for temperature measurement, a small aperture is preferred. However, the small aperture reduces the transmission of light greatly, causing the intensity of outcome light to be too weak to induce Raman or fluorescence signal. It is reported that an increase of the aperture diameter from 20 to 100 nm could result in the transmission coefficient increase by a factor of 625 (60). Therefore, compared with apertureless NSOM, the aperture mode would have lower spatial resolution for temperature measurement. Frey et al. (61) improved the resolution to 25 nm by using a tip grown on an aperture probe. The excellence of this design is combined advantages of both aperture and apertureless NSOM. To date, little research has been conducted on temperature characterization and most of the applications are in the microscopy field and nanoscale manufacturing. Wilde et al. (62) reported a design of an infrared NSOM that operates without any external illumination. They employed the infrared evanescent wave emitted from the surface to construct the image of surface plasmons, and the setup was named thermal radiation scanning tunneling microscope. As an example for the application in nanomanufacturing, Wang et al. (63) used the particular bowtie with nanoscale aperture to confine the laser light for the nanolithography.

4. Nanoscale resistance thermometry

Resistance thermometry is based on the temperature dependence of electrical resistance, which could be measured by monitoring the variation of voltage when the thermometer is applied with a low current. The most commonly used material in this technique is platinum.

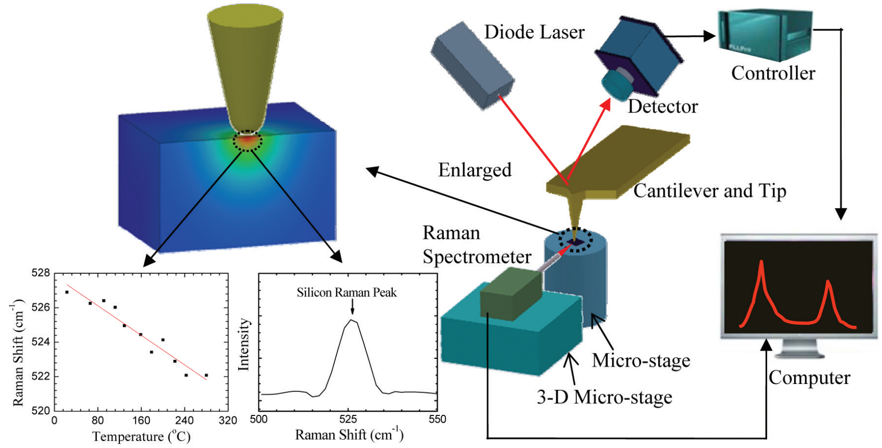

Fig. 5. Schematic of nanoscale temperature measurement under tip-induced near-field heating effect, sub-10 nm spatial resolution was obtained in this experiment. Reproduced with permission from Reference (9). American Chemical Society, Copyright (2011).

Based on the resistance thermometry, Guo et al. (64) developed an advanced thermal characterization method (transient-electro-thermal: TET) for measuring temperature and thermophysical properties of micro/nanowires. The extremely high accuracy of this technique has been verified by the calibration experiment using platinum wires, and tremendous works have been dedicated to the applications of this technique on various materials, for example, single polyacrylonitrile wires with diameters down to 324 nm (65) and TiO_2 nanotube arrays (66). To realize nanoscale temperature measurement by using the resistance thermometry, the sample acting as a thermal probe should be fabricated to nanosize. The probe will be suspended on a micro device and the electrical contact resistance at the ends should be minimized to reduce the measurement uncertainty in temperature determination.

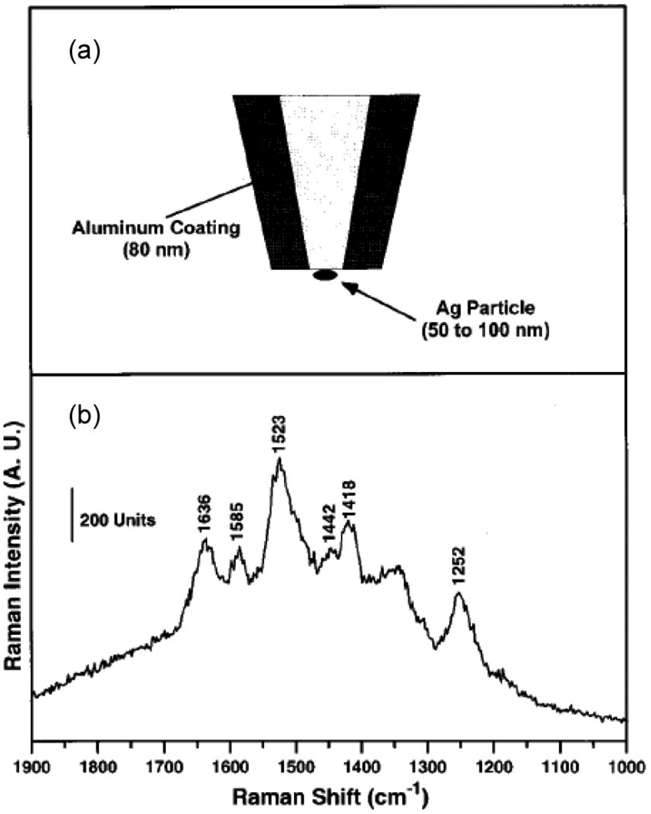

Fig. 6. (a) The diagram of single Ag nanoparticle attached to the tip for the near-field effect; (b) Enhanced Raman spectrum of the sample (3-hydroxykynurenine). Reproduced with permission from Reference (57). American Chemical Society, Copyright (1997).

Carbon nanotubes have excellent thermal and electrical properties, thus they are a good candidate for serving as resistance thermal probe, with a wide range of sensitivity, fast response and good stability (67–69). Kuo et al. (67) used nanoparticles as catalyst to grow CNTs bridging electrodes and fabricate a temperature sensor. In their work, the resistance of a CNT is in linear relationship with temperature, therefore the temperature can be determined by monitoring the resistance change of CNT. Besides CNT, other materials with temperature dependence of resistance can be used as temperature sensors, such as silicon nanowires, as shown in (Fig. 7a) (70).

It should be noticed that the temperature coefficient of resistance might not be constant (69). Figure 7b shows that the resistance of multi-walled CNT film has nonlinear relationship with temperature. Therefore, the calibration of temperature coefficient of electrical resistance should be conducted in advance. The probing resolution of this resistance method depends on the size of the thermal probe. The highest resolution achieved in Kuo et al.'s (67) work is 600 nm, which is not enough for nanoscale temperature sensing. Since this method depends on the intrinsic property of materials, samples with any small size can be used as temperature sensors. Consequently, the spatial resolution can be further improved. The main challenge for higher spatial

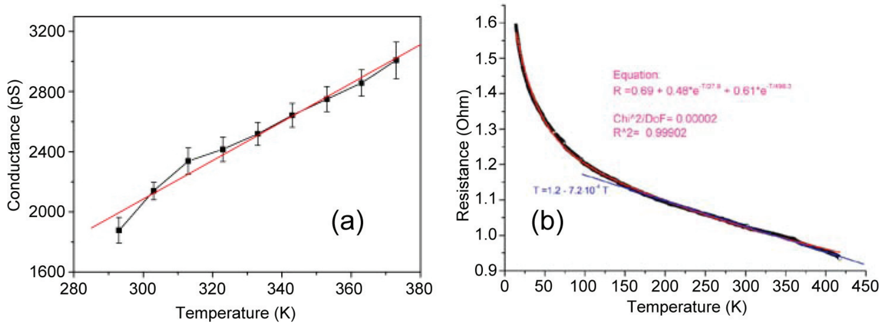

Fig. 7. (a) The conductance of silicon nanowires is in linear relationship with temperature; (b) Temperature dependence of resistance of CNT film, the temperature coefficient of resistance changes with temperature. Reproduced with permission from Reference (70) and (69). Elsevier, Copyright (2008) and American Institute of Physics, Copyright (2009).

resolution is the fabrication of electrodes and the synthesis of nano-sized materials, which require higher level nanolithography techniques.

5. Comparison of nanoscale thermal probing methods

Limitation and restriction of these methods, as well as various experimental conditions should be considered when applying these methods to nanoscale thermal probing. Among these methods, the scanning thermal microscope is most frequently employed in materials characterization and micro/nanoscale manufacturing in both academic research and industrial applications. Its long-term development, as well as its systematic apparatus in sample characterization, especially the evolution of various temperature sensors and platforms, make it very competitive in nanoscale thermal characterization and capable for applications under various experimental conditions. The feature size method is an important part in nanoscale thermal probing. It is very special because it realizes nanoscale temperature probing from another perspective: the measuring target. This method has been broadly applied in biology field to meet the challenge for surface imaging with dimensions down to single molecule. The main obstacle for its broader application comes from the preparation of nano-scale temperature sensors (the target) as well as the precise control of measuring locations. The near-field optical method effectively breaks the diffraction-limit barrier, producing an enhanced optical field within a very small region. This optical field is a unique source for nanoscale temperature measurement by using the Raman or fluorescence method. On the other hand, the strong optical field would induce intensive heating that is undesirable for some applications. Therefore, the possible low heating effect on the sample and enough light intensity for the near-field enhancement to make Raman/fluorescence signal detectable are tradeoff factors and should be considered case by case in different applications. The resistance thermometry is the easiest one to understand but the most difficult one to achieve deep sub-μm resolutions. It is because the temperature measurement is mainly based on the intrinsic resistance response to the heating effect of a nanoscale material. The temperature sensor requires high stability of its resistance and its dimension needs to be as small as possible to achieve high spatial resolution. Therefore, a small sensor with excellent temperature sensitivity is most desirable, thereby requiring advanced nanofabrication technique.

6. Conclusion

In this review, various techniques used in nanoscale temperature measurement, including the scanning thermal microscope (SThM) method, optical feature size method, near-field optical measurement and resistance thermometry technique were discussed for their measurement mechanism, spatial and temporal resolutions, as well as their applications. Among these techniques, the SThM technique has broad applications while its spatial resolution is limited by the size of the thermal probe. The feature size method has great potential if it is combined with the SThM technique. The near-field optical method has the unique capability of super high resolution down to sub-10 nm while an external excitation laser is needed. The electrical resistance method is becoming a good option for nanoscale temperature probing with the fast development of nanofabrication techniques. In summary, nanoscale temperature measurement is critical to the development of nanotechnologies while the development of nanofabrication techniques could, in turn, significantly advances nanoscale temperature measurement to higher resolutions and accuracy.

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Conflict of interest and funding

There is no conflict of interest in the present study for any of the authors.

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