Thermal imaging of nickel wires with a fluorescent nanoprobe

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Abstract. We have developed a scanning thermal microscope (SThM) that uses a fluorescent particle glued at the end of an atomic force microscope tip as a thermal sensor. When a temperature change occurs, a modification of fluorescence is detectable, enabling measurement of local temperatures and rendering of thermal images. We describe the technique and demonstrate its capability to map surface temperatures by measuring the local resistive heating in a 500nm wide nickel wire.

1. Introduction

Due to their incessant size reduction, microelectronic devices increasingly suffer from high temperature elevations that both diminish their lifetime and induce power dissipation problems. To optimize the design of chips, it is therefore more and more essential to observe the behavior of devices in operating conditions, and in particular their performance when facing up to intense thermal stresses. The development of scanning thermal microscopes (SThM) [1-3] has enabled the thermal characterization of such circuits, with a submicron lateral resolution. In these systems, the probes incorporate a small sensor that measures the value of a parameter (e.g. electrical resistance, voltage, or current) that varies with temperature. The most popular techniques use thermoresistive probes or thermocouple probes. The former one determines the temperature or the thermal conductivity by measuring the electrical resistance of a platinum wire in contact with the surface [2]. The latter one, namely the thermocouple junction [3], converts local temperature changes into voltage variations.

In this communication, we describe a new kind of temperature sensitive detection technique. It consists in using a small fluorescent particle glued at the end of an atomic force microscope (AFM) tip as a temperature sensor [4]. Due to the submicron size of the particle, an excellent lateral resolution can be achieved, allowing us to study the thermal behavior of small devices and circuits. In the following, we will first describe the experimental set-up. Afterwards, we will illustrate the possibilities of the technique by showing the temperature distribution in a resistively-heated 500nm-wide nickel wire.

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2. Principle of the experiment
The fluorescent material we use as a temperature detector is an erbium/ytterbium codoped fluoride glass. This compound possesses multiple absorption and emission lines in the visible and the near-infrared domain of the electromagnetic spectrum. Two erbium emission lines, located near 520 nm and 550 nm, are of particular interest because they are in thermal equilibrium. Their relative population, and hence their relative integrated intensity, directly depends on the temperature according to a law of the form [5]:

\[
\frac{I_{520}}{I_{550}} \propto e^{-\frac{\Delta E}{kT}}
\]

where \(I_{520}\) and \(I_{550}\) are the integrated intensities of the two fluorescence lines, \(\Delta E\) is the energy separation between the two levels, \(k\) is the Boltzmann constant and \(T\) is the temperature. Therefore, if we know the intensity ratio of the two fluorescence lines, we know the temperature. The photoluminescence (PL) spectra of the material under a 975 nm excitation (anti-Stokes excitation process) are given in figure 1 for temperature values of 24°C and 76°C. When the temperature is raised, the intensity of the 550 nm peak decreases due to its depopulation towards the adjacent high energy level (at 520 nm). Simultaneously, the intensity of the two peaks decreases due to the enhancement of non-radiative recombinations.

![Figure 1. (color online) PL spectra of the material at 24 and 76°C.](image)

![Figure 2. Scanning electron microscope image of a tip.](image)

To develop the scanning probe, the bulk fluorescent material is reduced to a small powder and a single submicron particle is glued at the end of a tungsten tip following the procedure described in [6]. A scanning electron microscope image of the tip, showing the particle at the extremity, is given in figure 2. The tip is then placed in a homemade AFM on which the sample is positioned. A sketch of the experimental set-up is given in figure 3. During the scan, the tip/sample distance is maintained constant in the tapping mode: the tip oscillates on the surface in intermittent contact with an amplitude of ~10-20 nm at a frequency of ~6 kHz. The excitation of the particle is performed with an intensity modulated laser diode (\(\lambda = 975\text{nm}\)) directed to the tip/surface region under oblique incidence. The collection of the photoluminescence is performed with a microscope objective and the light is sent to two photomultiplier tubes. Three images are acquired simultaneously: the sample topography and the fluorescence images of the particle at two wavelengths (520 nm and 550 nm). The thermal image is simply obtained by dividing the two optical images followed by a scale conversion with equation (1).

3. Analysis of the fluorescence variations on a 500 nm wide nickel wire
In order to evaluate the imaging capabilities of the technique, we tested it on a submicron wide planar nanoh heater device. The structure (an optical image is given in the inset of figure 3) consists of a nickel stripe (width = 500 nm, length = 80 \(\mu\) m, thickness = 40 nm) connected to two large nickel pads. It was fabricated using electron beam lithography and lift-off on top of a silicon substrate covered by a
500nm-thick SiO₂ layer realized by wet thermal oxidation. The structure was passivated by a 50nm thick sputtered layer of SiO₂.

**Figure 3.** Description of the experimental set-up. The inset shows an optical image of the device studied.

The experimental fluorescence images of the particle obtained when scanning the device are presented in figure 4. The study was realized on a 7×10µm² zone of the heater located at the interconnection with the pad. Two sets of images, for DC electrical current values equal to 0mA and 3mA were acquired. The top and bottom images represent the fluorescence at the two wavelengths (520nm and 550nm) respectively. The curves displayed on the right side of each image represent the average of the signal on 20 adjacent columns of the right side of the structure.

**Figure 4.** (color online) Fluorescence images of the particle when scanning the device: \( \lambda = 520\text{nm} \) (top) and \( \lambda = 550\text{nm} \) lines (bottom) for \( i = 0\text{mA} \) (left) and \( i = 3\text{mA} \) (right). The curves are vertical linescans extracted from the figures. The scales are arbitrary.

When no current circulates in the stripe, the two fluorescence images at 520nm and 550nm exhibit the same features. We observe an increase of the fluorescence above the nickel surface and a lower signal above the substrate. The illuminating laser light and the fluorescence are reflected differently on each material giving the observed contrast. A shadow is also visible on each side of the stripe, more
significantly on the bottom side of the 520nm image. When a 3mA current circulates in the device, the contrast of the 520nm image remains similar, but the 550nm line is strongly affected. A drop of the fluorescence is clearly visible when the particle is positioned on the stripe. This decrease is likely due to a change in the stripe temperature. It is consistent with the measured PL spectra presented in figure 2 that showed that the 550nm line was more sensitive to temperature than the 520nm one.

Figure 5. (color online) Ratios $I_{520}/I_{550}$ of the fluorescence images for $i=0mA$ (left) and $i=3mA$ (right). The curves represent vertical linescans extracted from the figures. The intensity scales are given both in arbitrary units and in °C.

Since the two fluorescence lines are in thermal equilibrium, it is possible to determine the temperature by dividing the image at 520nm by the one at 550nm and by converting the intensity scale to temperature with equation (1). The ratios are represented in figure 5 for $i=0mA$ and $i=3mA$. The left image, obtained at $i=0mA$, does not reveal any significant contrast, showing that the fluorescence difference on the materials at the two wavelengths is almost cancelled at room temperature. This image, which is our reference image, indicates that a contrast of ~11 corresponds to room temperature (25°C). Oppositely, the right image, obtained at 3mA, clearly reveals the temperature elevation in the wire only. The temperature can be determined by dividing the value of the contrast at $i=3mA$ (~14) by the one at $i=0mA$ (~11). With equation (1), we estimated the maximum temperature to be ~50°C with an uncertainty of ~5°C. Let us note that this value represents the temperature of the fluorescent particle, which is probably lower than the real nickel stripe one. The determination of the real temperature requires the knowledge of the different thermal transfer mechanisms between the surface and the probe which are very complicated in our case because our tip/sample regulation mode is the tapping mode. We are currently studying these transfer mechanisms in detail by making tip approach/retraction curves and by varying the oscillation amplitude of the tip. Finally, regarding the lateral thermal resolution, we can reasonably think it is close to the fluorescent particle size (~500nm). Therefore, the slow decay of the temperature outside the stripe is not due to a lack of resolution but rather corresponds to heat diffusion inside the SiO$_2$/Si substrate and in the passivation layer.

4. Conclusion
We have developed a technique that allows to directly visualize the heating of microelectronic devices with a submicron lateral resolution. This method is relatively simple to implement, and we next plan to use it to study thermal effects in nanodevices and heat transfer phenomena on submicron scales.

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