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Thermal imaging of hot spots in nanostructured microstripes

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Thermal imaging of hot spots in nanostructured microstripes

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Abstract. By scanning thermal microscopy, we study the behavior of nanostructured metallic microstripes heated by Joule effect. Regularly spaced indentations have been made along the thin film stripe in order to create hot spots. For the designed stripe geometry, we observe that heat remains confined in the wire and in particular at shrinkage points within ~1µm^2. Thermal maps have been obtained with a good lateral resolution (< 300nm) and a good temperature sensitivity (~1K).

1. Introduction

Understanding heat propagation mechanisms in micro and nanostructures is an important challenge for the development of nano-electronic devices and nanosystems since downscaling the circuits makes the power dissipation difficult. To improve their performances, it is therefore important to control the way they evacuate heat in the environment. On another hand, thermal devices like nanoheaters may have many applications in biology for controlling the motion of molecules and proteins. The temperature elevation in such devices as well as the way heat is spreading in the unheated zones of the structure also needs to be understood and controlled precisely [1,2].

In order to understand such phenomena, we have fabricated nanostructures that generate submicron hot zones and have characterized them with a scanning thermal microscope. The sample is a metallic microstripe in which several shrinkage points have been created. Since the current density in the constriction is locally much larger, heat is produced in these zones and spreads in the whole structure. In section 2, we will shortly describe the sample and the measurement technique. In section 3, we will present thermal images of the structure and will analyze the heat confinement areas. We will show that heat can be concentrated in zones of 1µm^2 area with a good reproducibility and a good contrast compared to colder zones.

2. Sample description and experimental details

The sample is a titanium microstripe with a periodic nanostructured pattern whose aim is to create hot spots. On top of a thermally oxidized silicon substrate (SiO_2 thickness = 100nm), a photoresist pattern is made by e-beam lithography. A thin (50 nm thick) titanium film is then e-gun evaporated in UHV, and lifted-off. A scanning electron microscope image of the structure is presented in Fig. 1. Nine adjacent nanostructured constrictions (dimension 400×800nm^2) were made in order to check the reproducibility of the measurements. The stripe is connected to two large titanium contact pads, also fabricated by e-beam lithography.

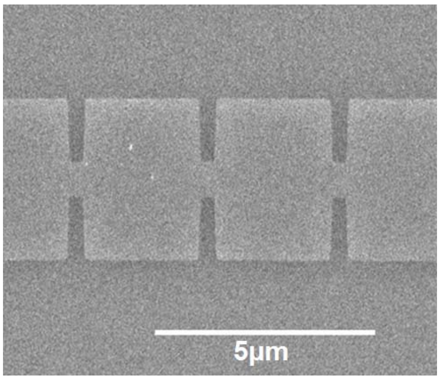

Figure 1. Scanning electron microscope image of the structure

The thermal characterization has been accomplished with a newly developed scanning thermal microscope whose specific sensor is a fluorescent particle [3,4]. The particle is glued at the extremity of a sharp atomic force microscope tip, and is excited by a laser beam [5]. Since fluorescence is a strongly temperature-dependent effect, the particle behaves like a tiny thermometer, able to map temperature variations at the sub-micron scale. The experimental set-up is depicted in Fig. 2. The sample is placed on an XYZ piezoelectric cube for scanning purposes. The tip oscillates on the surface in the intermittent contact mode, at about f=6 kHz with amplitude of 10nm. A laser emitting at λ=975nm is used to excite the nanoparticle by an up-conversion process. The fluorescence is collected in the visible at λ~550nm by a high numerical aperture objective placed just above the tip.

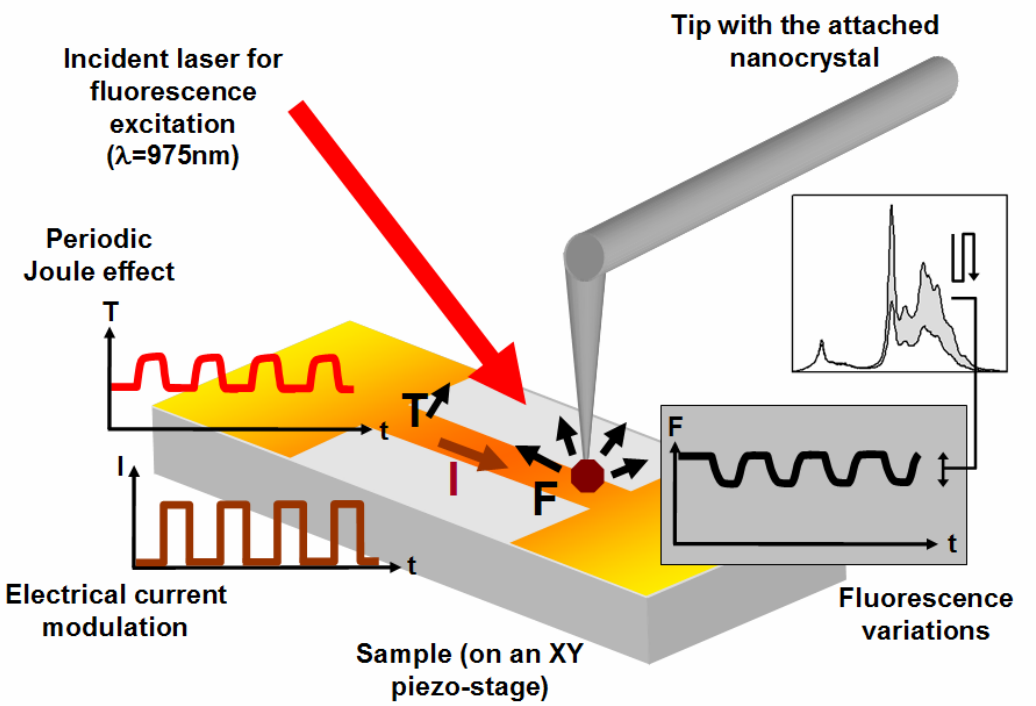

Figure 2. Experimental set-up: the device is powered by an ac current which modulates the stripe temperature. The thermal oscillations subsequently influence the particle fluorescence which acts as a thermometer. The fluorescence light is collected by a microscope and sent to a photomultiplier tube connected to a lock-in amplifier. The inset is a scanning electron microscope image of the structure.

3. Thermal imaging of hot spot in the microstripe

We show in Fig. 3 the topography, the fluorescence image obtained at room temperature (no current is circulating in the stripe) and the thermally modulated fluorescence images of the structure obtained when a current of amplitude 3mA is applied to the device.

The room temperature fluorescence image is a reference image. One can see that the particle emits more light on the metallic stripe than on the substrate. This effect has two origins. Firstly, the boundary conditions of the electromagnetic field are different on titanium and on silicon. Thus, the particle is excited by a field which depends on the nature of the material underneath. Secondly, the fluorescence light itself may be reflected to the detector differently if it is situated on a metal or on silicon. These effects create fluorescence variations that do not have a thermal origin, only an optical one. If we now observe the thermally modulated fluorescence image [Fig. 3(c)], we can observe that it is strongly different from the room temperature one. Three bright zones are visible and correspond to the shrinkage points. In these regions, the thermally modulated fluorescence is strongly enhanced and corresponds to an increase of temperature. In fact, the whole stripe heats up, but the current density is much higher in these zones than in the wide sections of the stripe, giving rise to the strong thermal contrast.

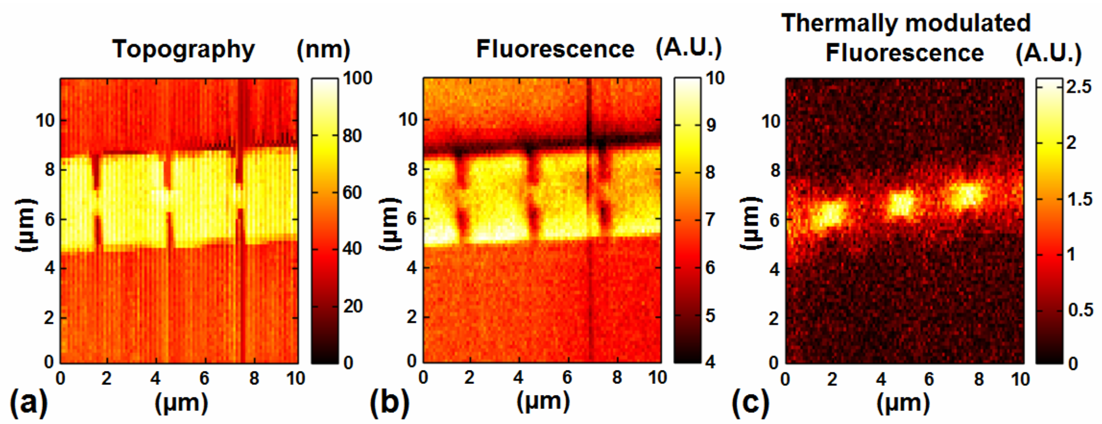

Figure 3. Topography of the structure (a), room temperature fluorescence (b) and thermally modulated fluorescence (c) of the particle. The topography corresponds to the room temperature fluorescence image.

The longitudinal and vertical cross-sections extracted from the thermally modulated fluorescence image are presented in Fig. 4. The cross-sections scales have been converted to temperature after normalization of the thermally modulated fluorescence signal by the room temperature fluorescence one [4]. This normalization allows to get rid of the local optical variations to only keep the thermal contribution [4]. For the studied structure, the lateral extension of the hot spots (the full width at half maximum) is ~1μm in both the longitudinal and the transverse directions. The lateral extension of the spots as well as the temperature strongly depends on the structure of the device. A good contrast is observed with the wider zones of the stripe for which the temperature elevation is smaller than 10K. It would probably be possible to ameliorate the heat confinement by using a metal that has a smaller thermal conductivity to avoid longitudinal heat spreading, and by reducing the thickness of the oxide to ensure a better contact with the silicon substrate and subsequently limit transverse heat diffusion. The influence of such geometrical and physical parameters of the structure is currently under development in our laboratory.

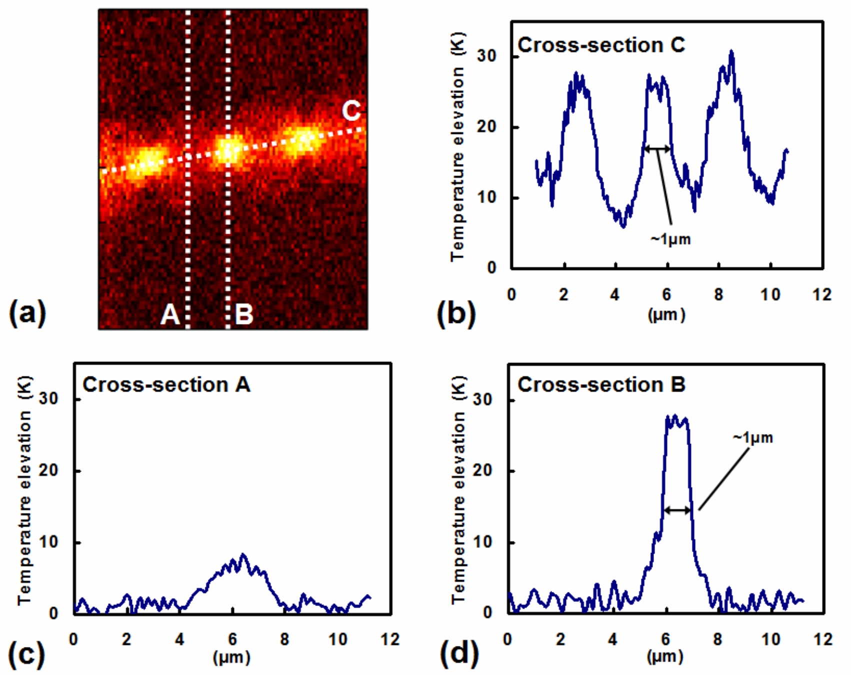

Figure 4. Thermally modulated fluorescence image (a), longitudinal cross-section (b) and vertical cross-sections along lines A (c) and B (d). The fluorescence variations have been converted to the temperature elevation in the stripe.

4. Conclusion

In this article, we have studied the heating of a nanostructured microstripe by scanning thermal microscopy. Hot spots localized in an area of the order of $1\mu m^2$ were created by reducing the size of the stripe periodically. Such structures may be of strong interest in biology, to create highly localized hot zones and to thermally initiate a chemical or biological reaction. In addition, such structures could be used in the domain of contact thermal lithography to modify the structure of a polymer and create patterns. The use of an electrical current to produce the heating is much easier than a highly focused laser beam. It does not necessitate costly equipments and avoid any diffraction problems.

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