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Quantitative temperature profiling across nanoheater on silicon-on-insulator wafer using null-point scanning thermal microscopy

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A B S T R A C T

With the rapid reduction in the characteristic length of electronic devices down to tens of nanometers in recent times, the characterization of self-heating in nanotransistors fabricated on silicon-on-insulator (SOI) substrates has become a major challenge. However, because of a lack of quantitative thermal characterization techniques at the nanoscale, analysis of the behavior of hotspots in a transistor has been performed mostly by theoretical modeling based on the Boltzmann transport equation, whose results are sometimes inconsistent. In this study, we use the recently developed null-point scanning thermal microscopy (NP SThM)—which can measure the quantitative undisturbed temperature simultaneously with the local spreading thermal resistance with nanoscale resolution—to simultaneously profile the undisturbed temperature distribution around an electrically heated 100-nm-wide platinum nanoheater patterned on an SOI wafer quantitatively and the local spreading thermal resistance qualitatively. Comparison of the experimental temperature and thermal resistance profiles with those obtained using the heat diffusion equation explains why the local temperature gradient and the absolute temperature are higher than the corresponding modeling results around the nanoheater. The quantitative data obtained in this study would be essential reference data for the validation of a theoretical model for thermal analysis in nanoelectronic devices. Furthermore, since NP SThM can profile the spreading thermal resistance simultaneously with the undisturbed temperature, it is expected to have wide applicability in the analysis of energy transport/conversion in nanodevices and nanomaterials.

1. Introduction

Rapid advancements in ultra large scale integration (ULSI) technology have reduced the characteristic length of electronic devices down to tens of nanometers. Because of such a drastic reduction in the device size, the self-heating problem of ULSI devices has become a bottleneck in the improvement of their performance and lifetime [1]. In ULSI devices, the extremely short channel length (~20 nm) results in an extremely large electric field, which creates optical phonons, and owing to their high energy and low group velocity, hotspots are generated [2]. These hotspots further exacerbate the local heating by increasing the local electrical resistivity, and ultimately lead to device failure. In particular, in the case of silicon-on-insulator (SOI) substrates, which are widely used for increasing the integration density, such hotspots become more critical because the thermal conductivity of the buried oxide (BOX) layer is very low (~1.3 W/m K) and the thickness of the silicon layer becomes comparable to or even much less than the mean free path (MFP) of phonon (~100 nm at 300 K) [3].

Theoretical and experimental studies on the temperature distribution around a hotspot have been conducted with the aim of analyzing the behavior of a hotspot in a transistor fabricated on SOI. Most of these studies have been theoretical and have predicted the behavior of a hotspot through approximate modeling based mostly on the Boltzmann transport equation (BTE) [3–6]. However, as demonstrated by Jin et al. [3] and Narumanchi et al. [4], depending on the adopted BTE model, such as the gray model, full dispersion model, and electron–phonon interaction model, the calculated temperatures of a hotspot are sometimes inconsistent. Therefore, it is crucial to acquire experimental data that can confirm the reliability of the modeling results. The need for such data has also been mentioned in the International Technology Roadmap for Semiconductors (ITRS) [7].

However, despite this significance and prolonged period of research, empirical studies on the behavior of hotspots in SOI

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transistors are surprisingly rare. Since the spatial resolution of conventional optical characterization methods such as the scanning thermoreflectance technique is about 1 μm, it is difficult to map out the temperature distribution around a hotspot in nanodevices whose characteristic length is less than 100 nm [8–10].

Owing to its high spatial resolution, scanning thermal microscopy (SThM) has been employed for locating hotspots and analyzing device failure through measurement of the temperature distribution on nanodevices [11]. However, the conventional SThM has three major problems: (i) distortion of the measured temperature profile owing to heat transfer through the air gap between the SThM probe and the sample surface [12]; (ii) difficulty in quantitative measurements owing to the unknown and sometimes variable value of the tip-sample thermal contact resistance, which depends on surface properties such as wettability and hardness; and (iii) perturbation of the sample temperature due to the heat flux through the tip-sample thermal contact [13]. Owing to these problems, even with its nanoscale spatial resolution, the conventional SThM has been used only for qualitative analysis and the obtained data have not been accepted as quantitative and reliable enough to serve as reference for BTE-based modeling results. Owing to these limitations on the spatial resolution and quantitative accuracy in direct temperature profiling, most experimental studies have focused on the measurement of the change in the thermal conductivity of the silicon layer in an SOI wafer as a function of its thickness by using the 3ω method [14] or a microthermometer [15–23].

Recently, with the aim of overcoming the aforementioned three major problems of the conventional SThM, null-point scanning thermal microscopy (NP SThM) has been developed. Since NP SThM measures the temperature of a sample at thermal equilibrium, where the temperature of the probe tip becomes equal to that of the sample surface and the heat flux between the probe tip and the sample surface is nullified, NP SThM can overcome these three problems [24].

Furthermore, Hwang et al. [13] recently batch-fabricated performance-optimized SThM probes through thermal design based on a rigorous theory of quantitative measurement and demonstrated that the probes enabled low-noise NP SThM with a spatial resolution of about 40 nm [13].

In their study [13], Hwang et al. used a platinum heater patterned into a 4-probe configuration on a 300-nm-thick SiO_2 layer thermally grown on a silicon wafer. They demonstrated that the temperature can be profiled quantitatively with nanoscale resolution by NP SThM by comparing the measured and modeled temperature profiles. To measure the heat generated by the heater accurately, the heater was patterned into a 4-probe configuration, and to allow precise modeling of the temperature profile, a thermally grown SiO_2/silicon substrate with negligible ballistic transport and known thermal conductivity, was used.

In addition, by rederiving the principal equation of NP SThM from a new perspective of thermal resistance, they proved that NP SThM can simultaneously measure the undisturbed quantitative temperature and the local thermal resistance [13].

In the present study, by using NP SThM along with the performance-optimized probe NP SThM01 (TSP Nanoscopy), we quantitatively profile the undisturbed temperature across an electrically heated 100-nm-wide platinum nanoheater patterned into a four-probe configuration on an SOI wafer. In order to understand the influence of the thickness of the silicon layer on the heat diffusion in the SOI wafer, we obtain the temperature profiles for two different nanoheaters on SOI wafers with 45-nm- and 100-nm-thick silicon layers. Additionally, to investigate the influence of the heating power on the temperature profile, we also profile the temperature at three different heating powers for each nanoheater.

2. Principle of NP SThM

In a previous study, noticing that the temperature of the probe tip is the same as that of the sample when the heat flux between them is zero, Chung et al. [24] rigorously derived the principal relation of NP SThM:

$$T_s = T_{c1} + \frac{T_{c2} - T_{c1}}{T_{j1} - T_{j2}}(T_{c1} - T_{nc1}) = T_c + \varphi(T_c - T_{nc}) \tag{1}$$

where T_s, T_c, T_{nc}, and T_j are the temperature of the sample surface, the temperature measured by the SThM probe in the contact mode, the temperature measured by it in a nonthermal contact mode, and the difference between T_c and T_{nc}, respectively. In addition, the subscripts "1" and "2" denote the data measured in the passive mode and active mode, respectively.

Recently, by rederiving the principal equation of NP SThM from the new perspective of thermal resistance, Hwang et al. [25] rigorously proved

$$\varphi = \frac{T_{c2} - T_{c1}}{T_{j1} - T_{j2}} = \frac{R_c + R_s}{R_p} \tag{2}$$

where R_c, R_s, and R_p are the thermal contact resistance between the probe tip and the sample, the spreading thermal resistance of the sample, and the thermal resistance from the tip of the SThM probe to the surroundings through the probe, respectively. Eq. (2) clearly represents the physical meaning of φ, which was not apparent from the first derivation by Chung et al. [24].

The detailed derivation of Eq. (2) and the explanation of its physical meaning can be found elsewhere [25]. In this study, to understand Eq. (2) and use it, we present the derivation in brief.

In previous studies [26,27], it has already been proved rigorously that the difference between T_{nc}, the temperature measured by the SThM probe just before its tip makes contact with the sample surface, and T_c, the temperature measured by the SThM probe just after the tip-sample contact, is proportional to Q_{st}, the heat flux through the tip-sample thermal contact:

$$Q_{st} = \frac{(T_c - T_{nc})}{R_p} \tag{3}$$

Once the SThM probe tip makes contact with the sample surface, Q_{st} is proportional to the difference between T_s' and T_c. Therefore, we obtain

$$Q_{st} = \frac{(T_s' - T_c)}{R_c} \tag{4}$$

where we use the symbol T_s' instead of T_s, which is the undisturbed temperature of the surface before the tip-sample contact, since the temperature of the sample surface is disturbed by Q_{st} after the tip-sample contact.

On account of Q_{st}, the temperature of the sample surface changes from T_s to T_s', and this change in temperature is determined by the local spreading thermal resistance of the sample, R_s, i.e.,

$$Q_{st} = \frac{T_s - T_s'}{R_s} \tag{5}$$

By eliminating T_s' in Eq. (4) using Eq. (5), we obtain

$$Q_{st} = \frac{(T_s - T_c)}{(R_c + R_s)} \tag{6}$$

Now, combining Eqs. (3) and (6), we obtain