Supplementary Information: AFM-Thermoreflectance for Simultaneous Measurements of the Topography and Temperature

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1. Calibration of the AFM probe on tungsten line heater

For the quantitative temperature measurement with the AFM-TR technique, calibration was performed in following steps: (1) the relation between the resistance and the temperature of the tungsten line heater was obtained and (2) the relation between ΔQPD_R and the resistance of the tungsten line heater was derived. As can be seen from the sample image in the inset of Fig. S1a, a reference tungsten-line-heater sample was prepared for the calibration. This reference tungsten line heater (422 nm in width, 72 nm in height, and 80 μm in length) was heated up to 420 K over 2 hours in a furnace where a K-type thermocouple is placed nearby the sample. Then, the furnace was cooled down to room temperature very slowly over 12 hours, and the thermocouple temperature and the electrical resistance of the reference tungsten line heater were measured simultaneously. Because the cooling speed is extremely slow, it can be safely assumed that thermal equilibrium is achieved between the thermocouple and the reference tungsten line heater. In Fig. S1a, the temperature measured by the thermocouple and the corresponding electrical resistance of the reference tungsten line heater are plotted and the linear relationship between the temperature and the electrical resistance is observed. After the first step of calibration was completed, the reference sample is brought into contact with the AFM-Si-probe tip in the AFM platform. The contact point is the center point (in both length and width directions) of the reference tungsten line heater and the validity of this calibration step will be discussed in section 2. The second step of calibration was conducted also in the low vacuum condition (~2 mTorr). While applying current across the reference tungsten line heater, the resistance of the reference tungsten line heater and corresponding ΔQPD_R were recorded concurrently (see Fig. S1b). Through these successive calibration steps, the relationship between the temperature of the reference tungsten line heater and the ΔQPD_R can be derived as in Fig. S1c. The slope of the graph plotted in the Fig. S1c can be considered as the sensitivity of our thermometry which has value of 0.013 %/K.

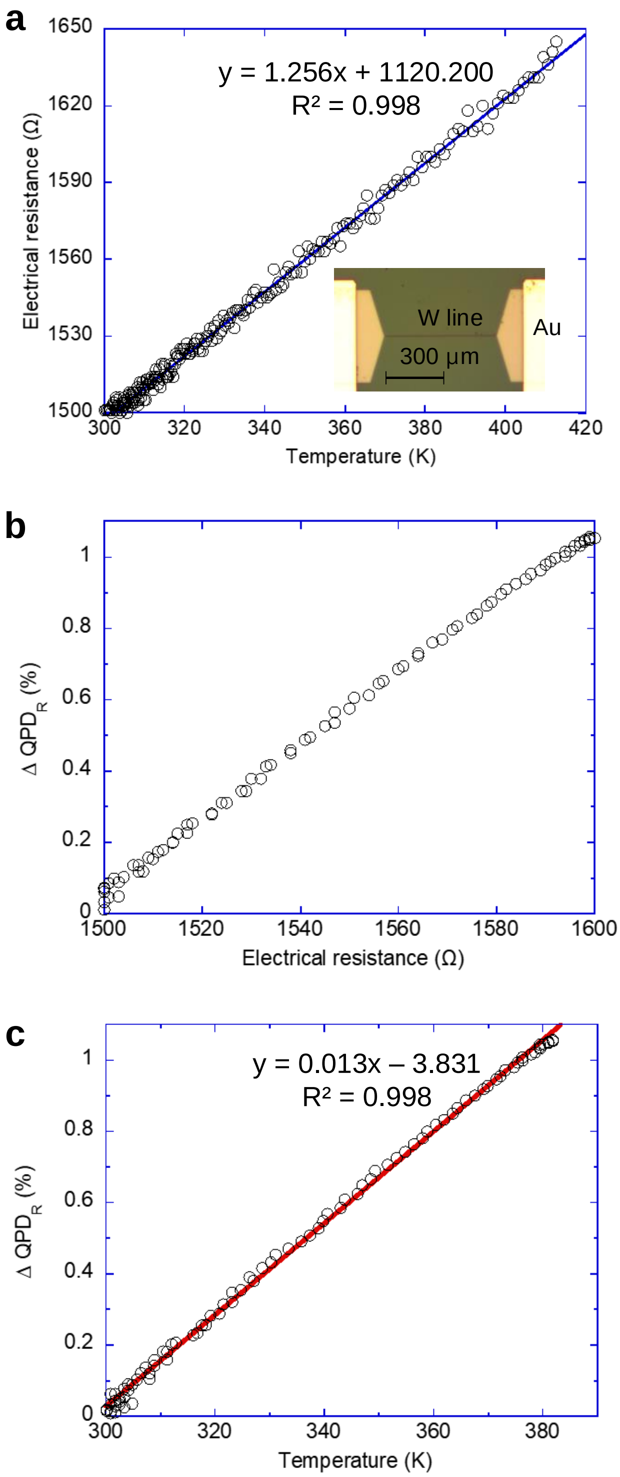

Figure S1. Calibration processes for the quantitative temperature measurement. (a) the electrical resistance of the tungsten line heater and the temperature obtained from the thermocouple in the furnace. (b) the measured ΔQPD_R and the electrical resistance of the tungsten line heater placed in AFM platform while applying Joule heating power into the line heater. (c) the relation between the temperature of the tungsten line heater and the corresponding ΔQPD_R derived from (a) and (b). The inset of (a) is the optical image of the reference sample.

2. Numerical modeling

The finite element method (FEM) analysis was performed with ANSYS software. The total size of the three-dimensional analytical model is 300 μm $\times$ 300 μm $\times$ 500 μm and the length of the tungsten line heater is set to 80 μm, which is the designed value. The cross-section of the tungsten line heater is assumed to be rectangular while ensuring that the cross-sectional area is identical to the measured trapezoidal cross-section (see Fig. 3 in main text). During the analysis, temperature-dependent properties are utilized and Joule heating is applied as an internal volumetric heat generation in the tungsten line heater. The ambient temperature is set to 298 K. The resulting temperature profiles obtained from the simulation are plotted in Fig. 3 (main text) in a cross-sectional view (midpoint in the length direction).

In the second step of calibration described in section 1, we obtained the relation between the temperature estimated from the electrical resistance of the tungsten line heater and the corresponding ΔQPD_R when the probe tip is in contact at the midpoint (in length direction) of the tungsten line heater to which Joule heating power is applied. In other words, the calibration is conducted between total average temperature of the tungsten line heater (i.e., derived from the electrical resistance) and the ΔQPD_R varied by the local temperature at the midpoint of the tungsten line heater. When Joule heating power is applied to the tungsten line heater, there should be a temperature distribution along the length direction of the tungsten line heater whereas it was uniform in the furnace where the first step calibration was conducted. In order to see how the local temperature at the midpoint of the tungsten line heater is different from the temperature obtained from the electrical resistance of the tungsten line heater (i.e., average temperature) under the Joule heating condition, FEM analysis using ANSYS software was performed and the resulting temperature distribution in length direction of the tungsten line heater is plotted in Fig. S2a for three different values of Joule heating power (i.e., 5.5 mW, 12.5 mW, and 19.5 mW). In 80-μm-long tungsten line heater, the temperature within central 64 μm is found to be nearly constant. The difference between the maximum and the minimum temperatures within this 64-μm-long tungsten line heater is predicted as following: 0.3 K for 5.5 mW, 0.7 K for 12.5 mW, and 1.0 K for 19.5 mW. Through the FEM analysis, it is found that the temperature is nearly uniform except for the 8-μm-section at both ends. When we compare the local temperature at the midpoint and total average temperature along the tungsten line heater, the maximum 0.9% difference can be estimated for the 19.5 mW input power. Fig. S2b shows the validity of the FEM simulation result. If we compare the temperature obtained from simulation and the temperature estimated experimentally from the electrical resistance under the same Joule heating condition, within the calibration range, the temperature difference between experiment and simulation was 2.3 K at maximum. Thus, it can be safely assumed that the FEM result is reliable and can represent the actual temperature distribution along the tungsten line heater.

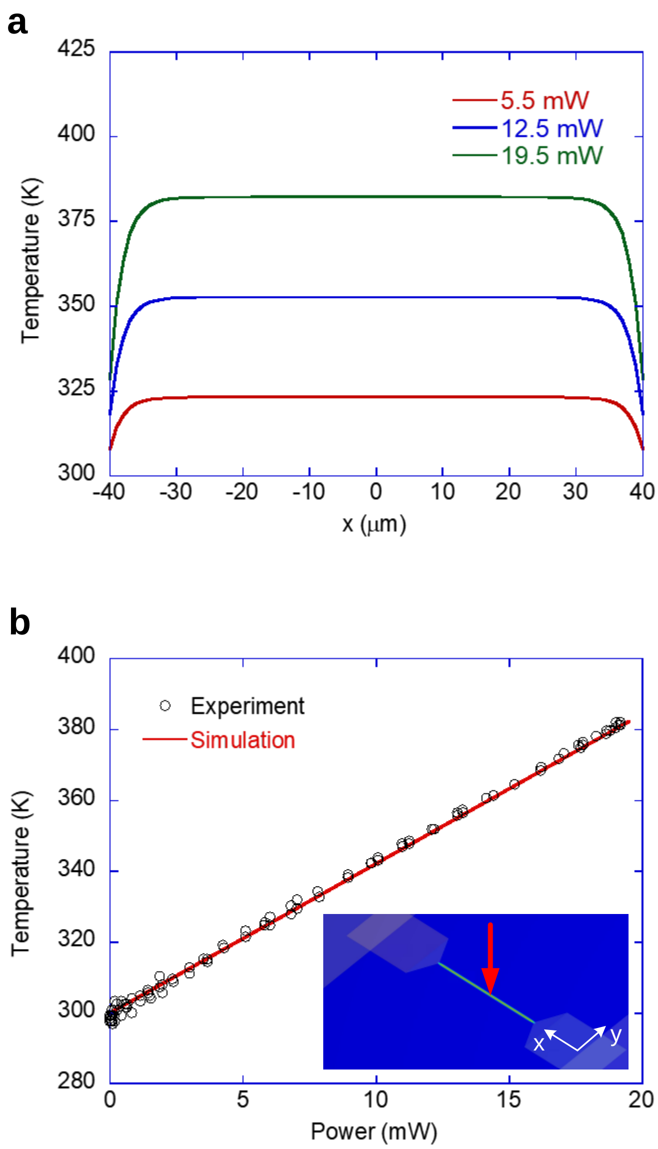

Figure S2. FEM simulation result obtained with ANSYS software. (a) Predicted temperature distributions along the length direction of the tungsten line heater under 5.5 mW, 12.5 mW and 19.5 mW of Joule heating power. (b) Comparison between the temperature of the tungsten line heater estimated by FEM analysis and the temperature of the actual tungsten line heater when applying power into the tungsten line heater. Inset to (b): the red arrow indicates the point where the simulation result is used.