ASTFE
American Society
of Thermal and Fluids Engineers

8th Thermal and Fluids Engineering Conference (TFEC)
May, 2023
Partially Online Virtual and at University of Maryland, MD

TFEC-2023-46023

ANALYSIS OF JOULE HEATING CHARACTERISTICS IN NANOWIRE NETWORKS MEASURED BY THERMOREFLECTANCE IMAGING METHOD

Kanji Tamai,[1,*] Yuta Sugihara,[1] Kazuya Tatsumi,[1] Reiko Kuriyama,[1] Kazuyoshi Nakabe[1]

[1]Kyoto University Kyodai-Katsura C-cluster-3, Nishikyo-ku, Kyoto 615-8540, Japan

ABSTRACT

Nanowire-network is a promising material for solar cells, touch panels, electronic devices, and neuromorphics. However, developing an evaluation method for the thermal reliability of these devices is a challenging issue and has not been fully solved. The present study aims to develop a model which can evaluate the Joule heating characteristics and the resulting temperature distribution of NW-networks. The NW-network consists of NWs of diameter 120-150 nm scattered on glass substrate in the area between electrodes with a gap of 100 μm. Electric current was applied periodically to the NW-network, and the temperature distribution was visualized using thermoreflectance imaging method 10μs after starting the heating. Overall temperature increase was observed in the NW-networks, where high temperature regions appeared especially along the energization paths accompanied by generations of hotspots at several specific connections of NWs. The probability density function (PDF) of the temperature was evaluated based on the Weibull plot. The distribution of the data could be divided into two regions: a high-temperature region with small slope and a low-temperature region with large slope. The high and low temperature regions were considered to represent the temperature increase caused by the Joule heating and heat transfer of the wires, respectively. We could also obtain good results in the aggression analysis using the mixed Weibull model. Further, we evaluated the effect of the number density of the NWs on the PDF of the temperature, and found that the slope of the Weibull plot in both temperature regions increased for the higher number densities.

KEY WORDS: Nanowire-network, Thermoreflectance imaging, Joule heating, Weibull model

1. INTRODUCTION

Nanowire(NW)-based transparent conductive electrodes are more flexible than existing ITO electrodes and are known for their high transparency due to their nanoscale wire diameter. NWs are expected to be applied to anti-fogging lenses, flexible touch screens, and solar cells. Such devices function by applying an electric current to a NW-network consisting of many interconnected NWs. However, since Joule heat is generated during operation, functional failure or damage due to electromigration or annealing caused by temperature rise is a problem. In this study, we measured the temperature distribution of NWs using the thermoreflectance imaging (TRI) method in order to understand the characteristics of the temperature change distribution when current is applied to the NW-network. The temperature change distributions were evaluated using the Weibull distribution, and the relationship between the temperature change distribution and the number density was quantitatively analyzed.

2. EXPERIMENTAL

The TRI method utilizes the fact that the reflectance of a sample surface changes with temperature to obtain the temperature distribution from the change in intensity value of the reflected light captured by a sCMOS

*Corresponding Kanji Tamai: tamai.kanji.33a@st.kyoto-u.ac.jp

camera when the surface of the sample is irradiated with light. In this measurement, the temperature was obtained from the difference between the intensity value of the reflected light from the sample at the reference temperature and the intensity value when the sample was heated to a high temperature. If the luminance value of the sample at the reference temperature is I_0, the intensity change is ΔI, and the sample temperature change is ΔT, the following relationship $\Delta I/I_0 = C_{\mathrm{TR}}\Delta T$. The thermoreflectance coefficient C_{TR} is a coefficient that depends on the wavelength of the material and the light, and the thermoreflectance coefficient of Ag used in this study at the irradiation light wavelength of 530 nm was -8.96$\times$10K^{-1} as a result of the pre-calibration.

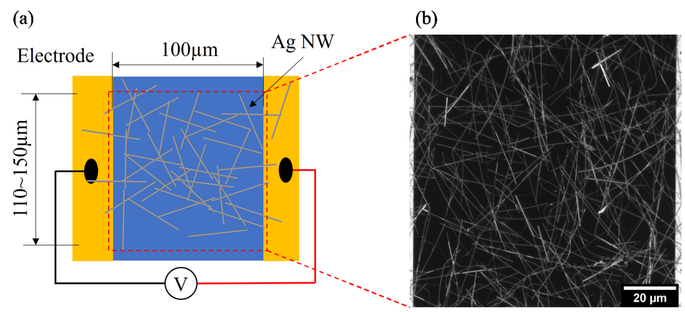


Fig. 1 (a)Schematic of Ag-NW network and electrodes on the SiO_2 glass substraate, (b)microscopy image of the Ag-NW network.

Fig. 1 shows a photograph of the sample and a schematic diagram of the temperature measurement method using the TRI method. In this experiment, parallel Au electrodes were deposited at 100μm intervals on a glass substrate, and Ag-NW (Sigma-Aldrich: 200-661-7) of 120-150nm in diameter and 20-50μm in length was spread over a 100μm wide area between the electrodes. Ag-NW was applied by vaccum filtration [1], and the density of Ag-NW was adjusted by changing the concentration of Ag-NW solution.

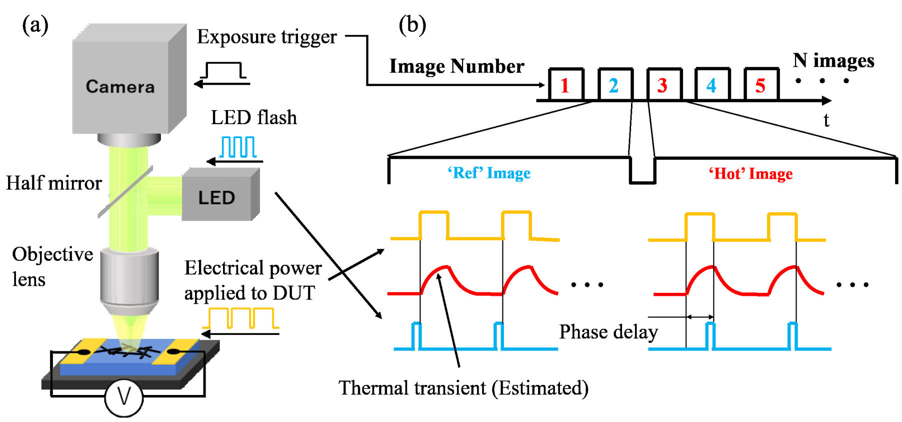


Fig. 2 (a)Schematic image of TRI measurement system, and(b)Time chart of the current, Thermal transient (Estimated), LED flash, and camera exposure.

Fig. 2 shows a schematic diagram of the experimental apparatus. In the experiment, a square wave voltage of 375 mV, application time of 10 μs, and period of 250 μs was periodically applied between both electrodes of the Ag-NW network, and the temperature distribution of the time phase was visualized 10 μs after the start of energizing by the TRI method. At each time point, the sample was exposed to pulsed light with an exposure width of 1μs, and 5000 images of the reflected light from the Ag-NW group were captured by an sCMOS camera (Hamamatsu Photonics: ORCA Fusion). To reduce the influence of the Ag-NWs' movement during imaging, the phase-limited correlation method was used to align the images, and the temperature distribution was calculated for each pixel. A 100x objective lens (Olympus: LMPLan FL 100X NA=0.8) was used to capture images. The area of the image is about 100$\times$100μm within the red frame shown in Fig. 1.

3. RESULTS AND DISCUSS

Fig. 3 shows the temperature distribution of Ag-NWs. The temperature distribution of the Ag-NW network can be considered as the spatial distribution of the energization paths, if we consider that the Ag-NW network is composed of energization paths and heat transfer paths by connecting NWs. The temperature distribution of the Ag-NW network can be considered as the spatial distribution of these paths. The Weibull distribution has been proposed as a method for evaluating the temperature distribution, and the Weibull distribution, which is usually used for lifetime prediction as a distribution with respect to time, is used for the evaluation of spatial characteristics.

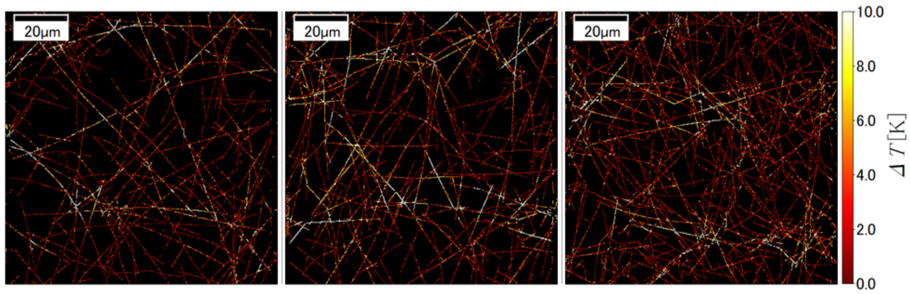
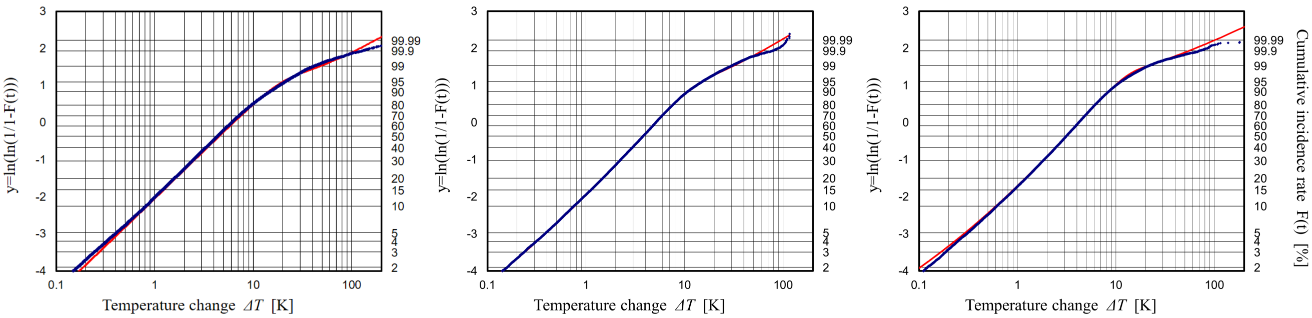


Fig. 3 The experiment result of TRI method,(a)temperature change distribution after heating 10μs L_{total}=67000μm,(b)L_{total}=77000μm,(c)L_{total}=100000μm,.

Fig. 4 plots the temperature distribution on the Ag-NW center line on Weibull probability paper. The results show that the temperature distribution can be divided into two regions: a high-temperature region with a small slope and a low-temperature region with a large slope. The high-temperature and low-temperature regions are considered to be caused by two phenomena, heat generation on the energization path and heat transfer from the heat generation line, respectively, and a mixture model that expresses them as superpositions is considered appropriate. Therefore, in this study, the mixture weibull distribution model with a mixture number of 2 shown in Eq. 1 was applied as the fitting function to the data in Fig. 3. The parameters a_i and m_i in the Weibull distribution are the Scale parameter and Weibull parameter. The parameters a_i and m_i are the scaling parameter and Weibull coefficient, respectively. i=1 and i=2 represent the low and high temperature regions, respectively. The Scale parameter a_i represents the degree of similarity of the temperature increase in the entire system, and the Weibull parameter m_i represents the degree of uniformity of the temperature distribution in the entire system. w is a weight parameter.

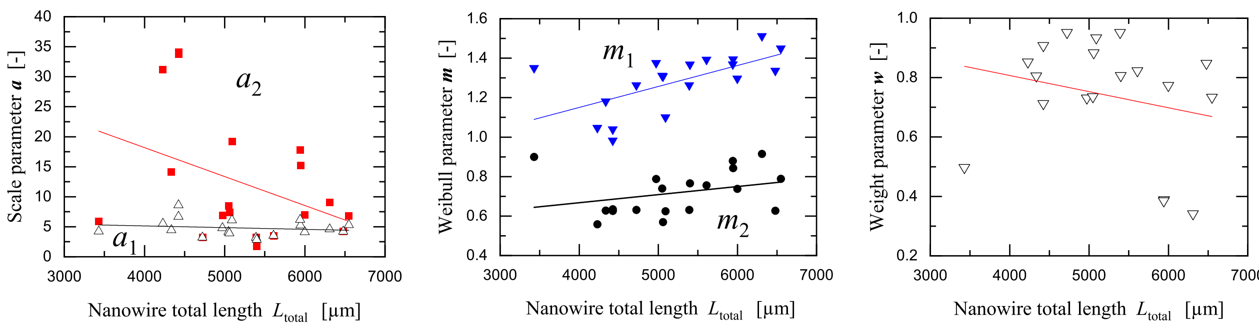
$$F\left(\Delta T\right) = w\left[1 - \exp\left(-\left(\frac{\Delta T}{a_1}\right)^{m_1}\right)\right] + (1-w)\left[1 - \exp\left(-\left(\frac{\Delta T}{a_2}\right)^{m_2}\right)\right] \tag{1}$$

Fig. 5 shows the relationship between the nanowire number density and the mixture weibull distribution model parameters. In Fig. 5(a), the Scale parameter a_1 in the low temperature region shows almost no change with number density, while the Scale parameter a_2 in the high temperature region shows a sharp downward trend. There are two possible reasons for this. One is the difference in the number of energization paths. The second reason is the heat transfer to the non energized Ag-NWs connected to the heat-generating part. Weibull parameter m in Fig. 5 (b) increases with number density for both m_1 and m_2, which is thought to be related to the fact that the temperature dispersion in the heated area becomes smaller and the temperature distribution approaches uniformity due to the increase in the energization path, and at the same time, the heat dissipation path increases. The increase in energization paths is also reflected in the change in the weight parameter in Fig. 5 (c), which decreases with respect to the number density, indicating a decrease in the number of non-energized nanowires. The weight parameter is around w=0.75-0.95, indicating the approximate percentage of nanowires in the energization path.



(a)L_{total}=67000µm (b)L_{total}=77000µm (c)L_{total}=100000µm

Fig. 4 Example of fitting results for each NW-network. The red lines are the curves of the mixture weibull distribution model used in the fitting.



(a)Scale parameter (b)Weibull parameter (c)Weight parameter

Fig. 5 Relationship between the parameters of the mixture weibull distribution model and the nanowire-total length L_{total} in the region.

4. CONCLUSIONS

The temperature distribution of joule-heated Ag-NWs was measured using the TRI method, and it was found that this was caused by two phenomena: heat generation on the energization path and heat transfer from the energization path to the non-energized wires. The results of experiments with samples of different wire number densities showed changes in each parameter, especially the Scale parameter a_2 in the high temperature region, which rapidly decreases with increasing wire number density and approaches the value of a_2. This is due to the increase in energization paths (dispersion) caused by the increase in the number of wires and the increase in heat transfer paths caused by the contact of non-energized nanowires with the heat-generating area. Since the effect of the increase in heat transfer (dissipation) paths due to the increase in energization paths on each mixture weibull distribution model parameter has not been separated, it will be necessary to combine the results with the numerical current distribution analysis results in the future.

REFERENCES

[1] Lee, P., Lee, J., Lee, H., Yeo, J., Hong, S., Nam, K. H., Lee, D., Lee, S. S., ”Highly Stretchable and Highly Conductive Metal Electrode by Very Long Metal Nanowire Percolation Network”, Adv. Mater., 24, pp.2526-2562, (2012).

[2] Suprem R. D., Amr M. S. M., Kerry M., Sajia S., Ali, S., David, B. J., and Muhammad A. A., ”Evidence of Universal Temperature Scaling in Self-Heated Percolating Networks”, Nano. Lett., 16, pp.3130-3136, (2016).