Gigantic Reduction of Energy Consumption of Molecule Sensors by Pulse-heating of Suspended SnO_2 Nanowire Device

Gang Meng, Kazuki Nagashima, Fuwei Zhuge, Masaki Kanai, Yong He and Takeshi Yanagida

Institute for Materials Chemistry and Engineering, Kyushu University

Integrating sensors for molecule species into portable electronic devices is strongly desired for forthcoming sensor network society. However, high energy consumption (~mJ) and high temperature (~300^{o}C) required for operating conventional gas sensors have been bottleneck issues to apply these for CMOS electronics and also emerging wearable electronics. Here we demonstrate a rational sensing methodology, which substantially reduces the energy consumption of gas sensors down to ~pJ/sec. Our methodology utilizes (1) a pulse self-Joule heating of suspended SnO_2 nanowire device and (2) the short thermal relaxation time down to microseconds. These features allow us to sense volatile molecules at the energy consumption of ~pJ/sec via heating up only the local sensing part within a short time by applying a pulse voltage. We show the feasibility of the present methodology for sensing NO_2 (100ppb) by applying a pulse voltage down to microseconds. Surprisingly, the sensitivity can be significantly enhanced by utilizing the present pulse method when compared with conventional continuous heating method. Furthermore, we successfully demonstrate the applicability of the present methodology for volatile molecule sensors on flexible PEN substrate.

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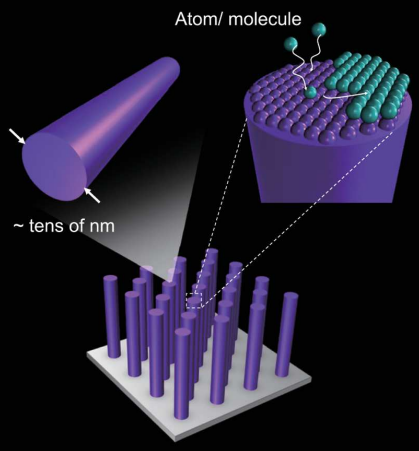
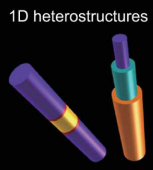
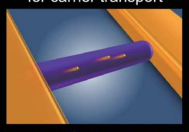
Introduction

Single-crystalline bottom-up nanowires

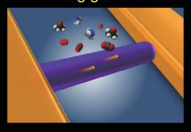




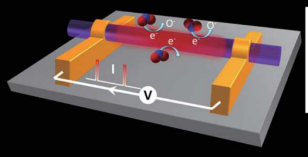
Single crystalline pathway for carrier transport



Large surface to react with surrounding gas molecules



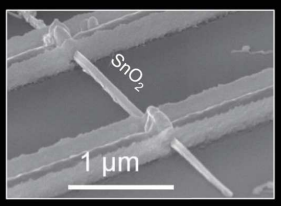
Opportunities offered by a suspended nanowire



- Small Joule power to heat it up $\Delta Q = c \cdot m \cdot \Delta T$
- **Short thermal relaxation time** $\tau_{relaxation} \propto \frac{C_p}{\kappa} l_0^2$

Objective:

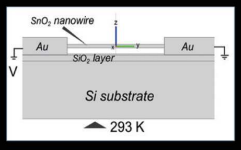
1) Evaluate heat transport in self-heated nanowire
2) Reduce energy consumption of sensor (<nJ/s)
3) Fully explore advantages of suspended nanowire device



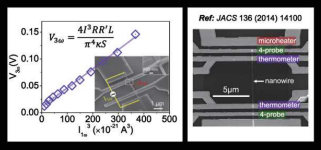
Result & discussions

Evaluate Joule heat in nanowire

- Simulation model -



- Extract $\kappa_{nanowire}$ by 3ω method -



Specific heat capacity — Thermal conductivity

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k\nabla T) = Q$$

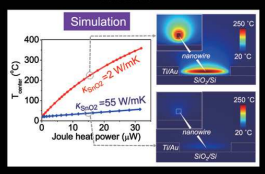
Density — Heat sink (Joule heat)

SnO_2 bulk [100]	55 W/mK
SnO_2 [100] nanowire	~ 2 W/mK

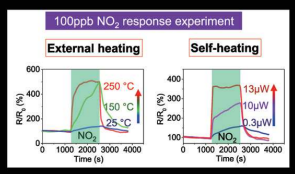
Thermal conductivity κ maybe crucial

Reduced $\kappa_{nanowire}$ (increased phonon scattering)

- Impact of $\kappa_{nanowire}$ on self-heating -



- Model verification -



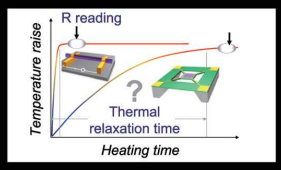
Effective self-heating in nanowire (low κ)

13 μW --- ~250 °C

☐ Low $\kappa_{nanowire}$ facilitates localization of Joule heat within nanowire

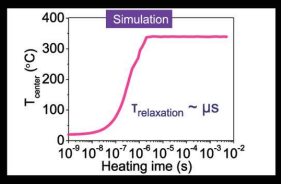
Reduce Energy consumption

- Concept: pulse measurement -

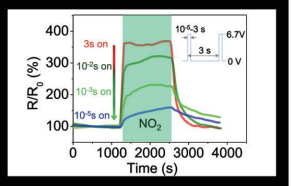


Read R just after temperature raising

- $\tau_{relaxation}$ -

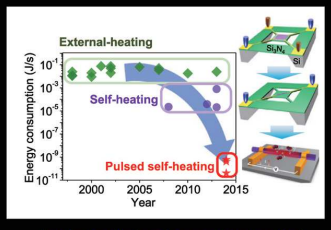


- Pulsed self-heating -



Showing response by a pulse (10 μs) heat

- Summary of energy consumption -

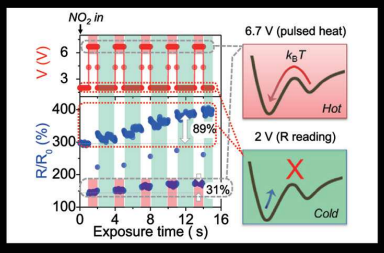


5 orders reduction of energy consumption!

☐ Short $\tau_{relaxation}$ enables a drastic reduction of energy by pulsed mode

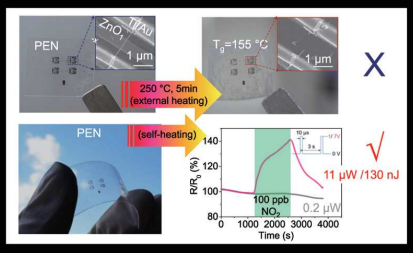
Further merits provided by pulsed self-heating

- Higher sensitivity -



☐ Manage heat & R reading --- high S

- Good compatibility with flexible substrate -



☐ Overcome the bottleneck of working temperature

- Ultra-fast temperature modulation -

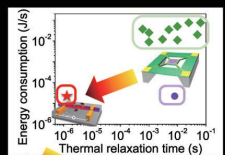
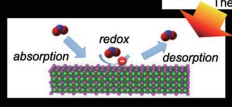


Exhibit the lowest $\tau_{relaxation}$



Ultra-fast gas/oxide interaction kinetics

☐ New feature to distinguish gas molecules