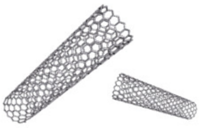

# DEVELOPMENT OF MWCNT EMBEDDED MICROMECHANICAL RESONATOR WORKING AS RAREFIED GAS SENSOR


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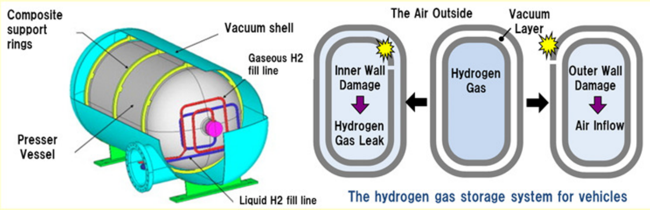
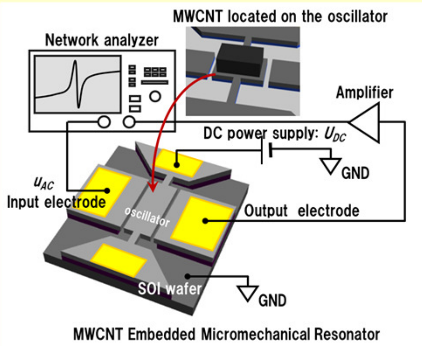
*ABSTRACT* **:** This research has newly developed **the multi-wall carbon nanotubes (MWCNTs) embedded-micromechanical resonator working as a novel rarefied gas sensor**. The inertial effect of rarefied gas fluid is detected as a variation of the resonance frequency, and the dissipation of the interaction energy between the resonator and the gas molecules affects the damping of oscillation. Thus, two kinds of gaseous species can be distinguished with one device. The MWCNTs have been arranged on the resonator for heightening its sensitivity by the bio-MEMS compatible process. The MWCNTs embedded-resonator has successfully demonstrated to detect and distinguish hydrogen and nitrogen gases under pressures of 0.02 Pa to 0.9 Pa.

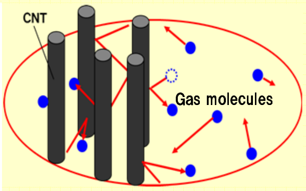

## Design And Process of MWCNTs Embedded Micromechanical Resonator

### Concept of Rarefied Gas Sensing




The objective of this research is to develop a novel rarefied gas sensor for a hydrogen gas storage system of vehicles. The MWCNTs embedded-micromechanical resonator can detect the inertial effect of rarefied gas fluid and the dissipation of the interaction energy between the resonator and the gas molecules.




Considering the case of a Newtonian fluid, the fluid force on the oscillating resonator is described in the following equation

$$R(t) = -m_i\gamma_f u - m_i\beta_f \frac{du}{dt} \qquad (2)$$

Rewriting Eq. (1) by the addition of Eq. (2), the following equation is derived.

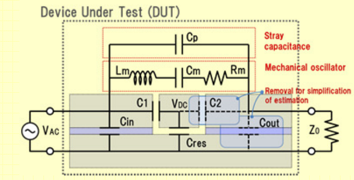
$$F\cos\omega t = m_i\frac{d^2x}{dt^2} + c\frac{dx}{dt} + kx + k_3x^3$$

$$= m_i\frac{d^2x}{dt^2} + c\frac{dx}{dt} + Kx \qquad (K = k + k_3x^2) \quad (1)$$

$$(1+\beta_f)\ddot{x} + (\gamma_i+\gamma_f)\dot{x} + \omega_i^2 x = F(t)/m_i$$

Therefore, the fluid can contribute to increases in both the effective mass and the dissipation of resonator.

### Equivalent LCR circuit model of Resonator




$$S_{21} = \frac{2Z_0Z_A(Z_m+Z_p)}{Z_0(Z_0+2Z_A)(Z_m+Z_p)+Z_mZ_p(Z_0+Z_A)}, \qquad (3)$$

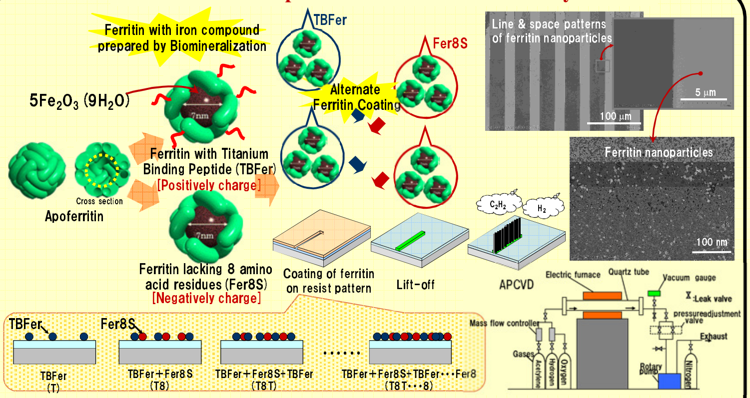
where,

$Z_m = R_m + j\omega L_m + \frac{1}{j\omega C_m}$, $Z_A = \frac{1}{j\omega C_A}$,

$Z_p = \frac{1}{j\omega C_p}$, and $C_A = \frac{C_1C_{res}}{C_1+C_{res}} + C_{in}$.

The equation of motion for the lumped mechanical model can be transferred into a simplified equivalent LCR circuit model. We has predicted the transmission amplitude $|S_{21}|$ as an output signal from the device using the Eq. (3) that is based on the LCR circuit model.

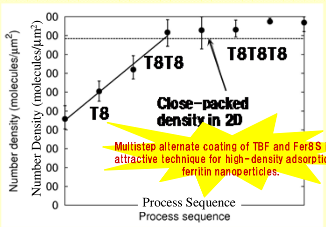
### Bio-MEMS Compatible Process for MWCNTs Synthesis

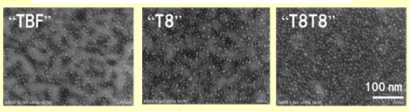



In order to arrange MWCNTs on the resonator, this study employed MWCNTs synthesis using the charge-controlled ferritin proteins coating process for APCVD. Ferritin protein is a 12-nm-sized protein molecule with a hollow structure of 7 nm that can contain a $5Fe_2O_3(9H_2O)$ nanoparticle. In this study, the iron composite nanoparticles inside ferritin molecules were used as catalysts to synthesize MWCNTs in APCVD.

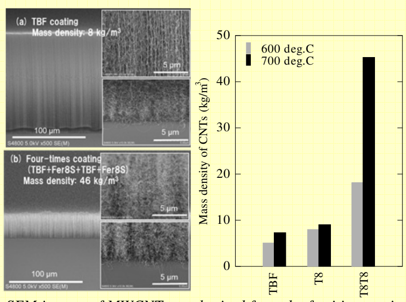
## Results and Discussions

### MWCNTs Synthesis



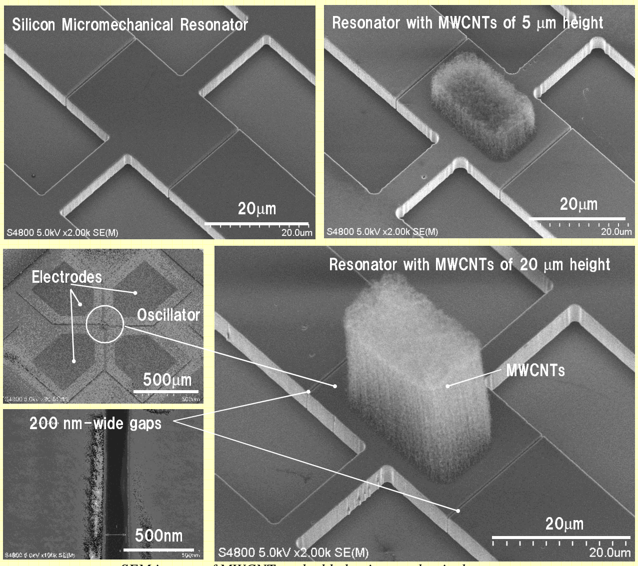

*Adsorption density with SEM images of ferritin proteins.*




*SEM images of MWCNTs synthesized from the ferritin protein catalysts; (a) TBF adsorption, and (b) multistep alternate adsorption of TBF and Fer8S.*

The density of the MWCNTs can be increased by an increase of ferritin density.

### Characteristics of MWCNTs Embedded Micromechanical Resonator




*SEM images of MWCNTs embedded- micromechanical resonator*

The transmission amplitude $|S_{21}|$ of the device was measured at the $U_{DC}$ of 50 V and the $u_{ac}$ of 0 dBm.

- The anti-resonance frequency ratios in $H_2$ and $N_2$ gases increase with an increase of the pressure. This is caused by the increase of the effective mass due to inertial effect of the gas fluid around the resonator. The ratio in $N_2$ gas also shows the larger change than that in $H_2$ gas under each pressure because of the difference between their molecular weight.
- The similar trend of the damping parameter $1/\xi$ is observed. The change of $1/\xi$ in $N_2$ gas is larger than that in $H_2$, which also depends on the molecular weight. From these figures, we can distinguish gaseous species of $H_2$ and $N_2$.