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Journal of Non-Crystalline Solids 316 (2003) 297–301

JOURNAL OF NON-CRYSTALLINE SOLIDS

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# Electrical properties of photo-CVD boron-doped hydrogenated nanocrystalline silicon-carbide (p-nc-SiC:H) films for uncooled IR bolometer applications

Hyung Kew Lee *, Seung Yeop Myong, Koeng Su Lim, Euisik Yoon

*Department of Electrical Engineering and Computer Science, Korea Advanced Institute of Science and Technology, 373-1 Guseong-dong, Yuseong-gu, Daejeon 305-701, South Korea*

Received 23 January 2002; received in revised form 9 May 2002

## Abstract

Electrical properties of boron-doped nanocrystalline silicon-carbide (p-nc-SiC:H) films grown by mercury-sensitized photo-chemical vapor deposition method have been investigated for uncooled IR bolometer applications. The temperature coefficient of resistance (TCR), conductivity, and $1/f$ noise characteristics have been measured and the detectivity of a bolometer has been estimated from them. It has been observed that as ethylene gas flow ratio ($C_2H_4/SiH_4$) increases, TCR of films increases due to larger optical bandgap. However, the $1/f$ noise also increases due to the reduction of the number of total carriers in the films for higher activation energy ($E_a$). The maximum TCR of 2.3%/K has been measured for the films deposited with an ethylene gas flow ratio of 0.47, while the maximum detectivity has been estimated for those with an ethylene gas flow ratio of 0.07 because of the lowest $1/f$ noise.

*PACS:* 73.61.T; 61.46; 73.50.T

## 1. Introduction

Great attention has been paid to uncooled infrared imaging systems for a wide range of applications, from military night vision to automotive and security systems, because of their low cost in comparison with their cooled counterparts. An uncooled infrared imaging system consists of an array of thermal detectors that converts infrared radiation into temperature changes. A bolometer, as one of the most successful thermal detectors, has been actively researched for imaging applications due to its possibility for low cost systems [1–5]. A bolometer is a resistive sensor that detects temperature changes by resistance change. Therefore, for high performance, a bolometer should be effectively thermally isolated from the substrate and sensing materials with high temperature coefficient of resistance (TCR) and low $1/f$ noise should be used.

In this work, we have investigated the electrical properties, especially TCR and $1/f$ noise, of boron-doped hydrogenated nanocrystalline

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* Corresponding author. Tel.: +82-42 869 8062; fax: +82-42 869 3410.

*E-mail address:* sanaii@iml.kaist.ac.kr (H.K. Lee).

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PII: S0022-3093(02)01630-7

silicon-carbide (p-nc-SiC:H) films prepared by using photo-chemical vapor deposition (photo-CVD) and estimated the performance of a bolometer using these films as a sensing material. A p-nc-SiC:H film is highly conductive and wide bandgap material which is a promising candidate as a buffer layer of amorphous Si:H solar cell [6]. Generally, it has a large TCR which can be controlled by adjusting the bandgap by changing carbon concentration during deposition. Since photo-CVD uses a UV light to dissociate the reactant gases, films can be usually deposited with small power (~10 mW/cm$^2$) and low substrate temperature ($\leqslant 250$ °C). This eliminates the possibility of ion damage during the film deposition, so that the grown films are expected to have smaller $1/f$ noise than those grown by PECVD method. From these reasons, p-nc-SiC:H films grown by photo-CVD are expected to be good sensing material for high-performance bolometer due to their high TCR, low noise, and low temperature process.

## 2. Experimental

Boron-doped hydrogenated nanocrystalline silicon-carbide films have been grown in a mercury-sensitized photo-CVD system using the mixture of silane ($SiH_4$), hydrogen ($H_2$), diborane ($B_2H_6$), and ethylene ($C_2H_4$) reactant gases on glass (Corning 7059) substrates. A low pressure mercury-sensitized lamp with optical resonance frequencies of 184.9 and 253.7 nm has been used as a UV source to dissociate the gases. The radiation enters the reaction chamber through a quartz window coated with fomblin oil to prevent the film deposition on the window itself. During deposition, hydrogen dilution ratio ($H_2/SiH_4$), diborane doping ratio ($B_2H_6/SiH_4$), chamber pressure, mercury bath temperature, and substrate temperature have been maintained at 20, 3000 ppm, 0.46 Torr, 50 and 250 °C, respectively. Four films have been prepared at various ethylene gas flow ratios ($C_2H_4/SiH_4$) of 0.07, 0.2, 0.33, and 0.47, respectively, while the film thickness is fixed at about 230 nm. To measure electrical properties we have deposited aluminum coplanar electrodes of various size on the top of p-nc-SiC:H films using a thermal evaporator. Taking the volume effect into account, we have formed four coplanar electrodes of different sizes on a sample with the $C_2H_4/SiH_4$ of 0.07.

The conductivity of the films has been measured in darkness as a function of temperature from 300 to 340 K to calculate the activation energy ($E_a$) of dark conductivity ($\sigma_d$) that is directly proportional to TCR. The Johnson noise and $1/f$ noise characteristics of the films over various bias conditions have been studied by using a HP35670A dynamic signal analyzer and an EG&G transimpedence amplifier.

## 3. Results

Fig. 1 shows the correlation between the resistivity and TCR of various films prepared in our previous work [6–8]. There is a strong linear relationship between the TCR and resistivity regardless of film deposition conditions. The TCR is severely affected by the resistivity and can be controlled by adjusting one of any process variables such as the $H_2/SiH_4$, $C_2H_4/SiH_4$, and $B_2H_6/SiH_4$. Fig. 2 shows the $\sigma_d$, $E_a$ and TCR changes of the prepared films as a function of the $C_2H_4/SiH_4$. As the $C_2H_4/SiH_4$ increases, the $E_a$ and also TCR

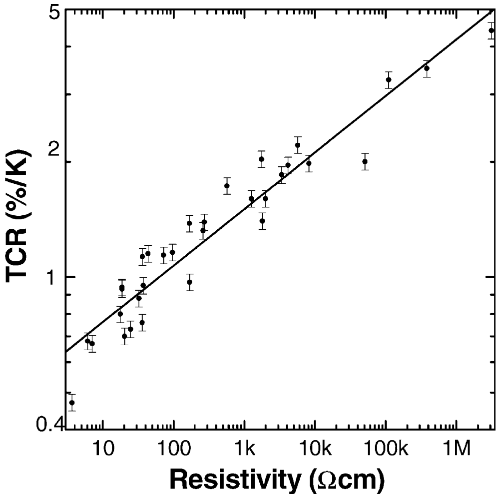

Fig. 1. Correlation between the resistivity and TCR of various p-nc-SiC:H films.

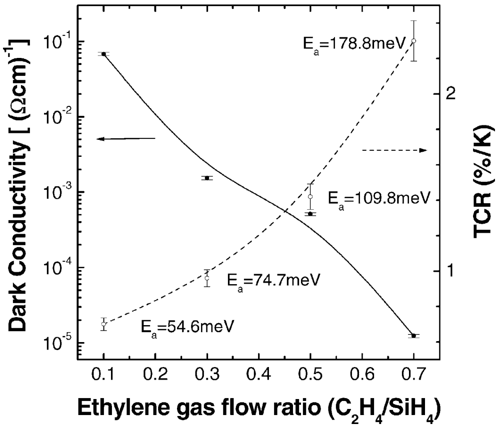

Fig. 2. Dependence of the $\sigma_d$, $E_a$ and TCR as a function of the $C_2H_4/SiH_4$.

increase because the TCR is directly proportional to the $E_a$. We have obtained the maximum TCR of 2.3%/K at 300 K for the film deposited with the $C_2H_4/SiH_4$ of 0.47. Its $\sigma_d$ of this film has been measured as $1.24 \times 10^{-5}$ $(\Omega\,\mathrm{cm})^{-1}$. Fig. 3 shows the noise power spectra of the same film as a function of bias currents. At no bias condition, only Johnson noise is dominant. Johnson noise does not depend on frequency or bias condition but depends on resistance and temperature. As bias current increases, the $1/f$ noise appears and becomes dominant. Generally, the $1/f$ current noise power spectrum of a homogeneous semiconductor film can be expressed by Hooge's experimental equation as follows:

$$S_I = \frac{\alpha}{N}\frac{I^2}{f} \tag{1}$$

where $N$ is the total number of free carriers, $I$ is the bias current, and $f$ is frequency [9]. The $\alpha$ is a Hooge's parameter, which depends on the quality of crystal and scattering mechanisms that determine the mobility [9]. The $1/f$ noise spectrum is inversely proportional to the volume of films as well as number of total free carriers. Fig. 4 shows the linear volume dependency of the noise power at 1 Hz as predicted by the Eq. (1). We measured the $1/f$ noise $(\alpha/N)$ of the four samples with different sizes and compensated the effect for the same size with this result. Fig. 5 shows the compensated noise spectra of the four samples at a 100 μA bias current as a function of the $C_2H_4/SiH_4$. As the $C_2H_4/SiH_4$ increases, the total carrier number decreases because of the increase of the $E_a$. Therefore, the $1/f$ noise $(\alpha/N)$ also increases.

The detectivity of a bolometer can be estimated by using the measured TCRs and noise spectra of the films for the thermal isolation structure proposed in Ref. [1]. The measured electrical parameters of the p-nc-SiC:H films and estimated bolometer performances are summarized in Table 1. While the maximum TCR has been measured as 2.3%/K with the $C_2H_4/SiH_4$ of 0.47, the maximum

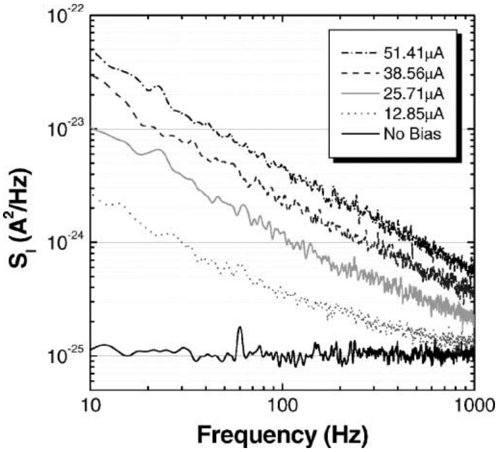

Fig. 3. $1/f$ noise spectra of the film deposited with the $C_2H_4/SiH_4$ of 0.47.

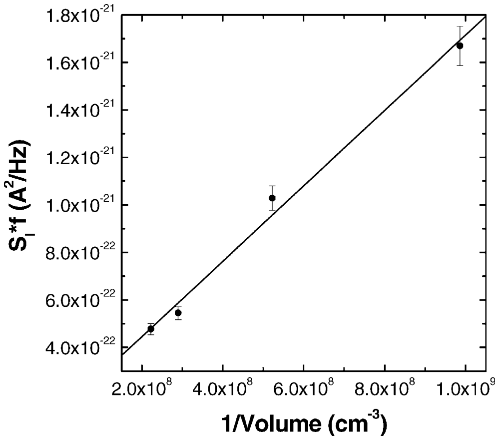

Fig. 4. Noise power of the film deposited with the $C_2H_4/SiH_4$ of 0.07 for various volumes at 1 Hz.

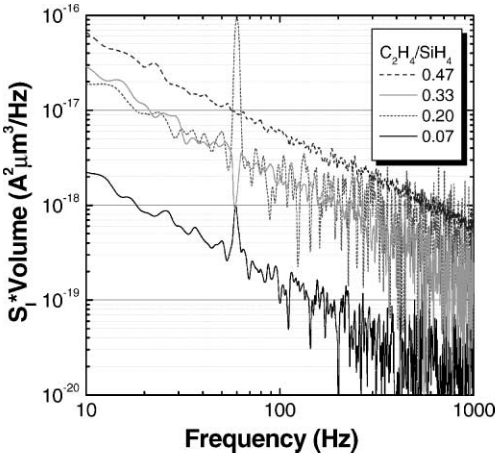

Fig. 5. Noise spectra of the four samples normalized by volume at a 100 μA bias current as a function of the $C_2H_4/SiH_4$.

estimated detectivity of $1.78 \times 10^8$ cm Hz$^{1/2}$/W has been estimated with the $C_2H_4/SiH_4$ of 0.07 owing to its the lowest $1/f$ noise.

## 4. Discussion

High carbon content prohibits the nanocrystallization of SiC:H films, and thus decrease the $\sigma_d$. On the contrary, the TCR of the films increases because of the increase of $E_a$. In order to provide an adequate deposition time and low temperature process suitable for bolometer applications, adjusting the $C_2H_4/SiH_4$ is the most effective way to control the TCR. Although the source of $1/f$ noise is debatable, it is generally accepted that the $1/f$ noise is a fluctuation in conductivity [9]. As shown in Table 1, whereas the $1/f$ noise ($\alpha/N$) increases by about two orders of magnitude, the $\sigma_d$ decreases by more than three orders as the $C_2H_4/SiH_4$ increases. The $E_a$ also increases. The extent of decreased carrier concentration induced from the increment of $E_a$ has been estimated more than two orders of magnitude, which seems the main reason for the increment of $1/f$ noise. However, $\alpha$ seems to decrease because of the decrease of structural non-uniformity [10]. The structure of p-nc-SiC:H films consist of nanosized crystal silicon (c-Si) grains embedded in amorphous SiC:H (a-SiC:H) matrix [6]. As the $C_2H_4/SiH_4$ increases, the p-nc-SiC:H films maybe becomes amorphous due to the reduction of the crystal volume fraction [6]. Hence the homogeneity of p-nc-SiC:H films increases and the crystal non-uniformity which causes the fluctuation of carrier concentration decreases [10].

As a result, there is a trade-off between TCR and $1/f$ noise in p-nc-SiC:H films as sensing material for a bolometer. It is desirable to reduce $1/f$ noise because the $1/f$ noise determines the ultimate performance of a bolometer.

## 5. Conclusions

We have investigated the electrical properties of p-nc-SiC:H films for bolometer applications. As the $C_2H_4/SiH_4$ increases from 0.07 to 0.47, the TCR increases from 0.7%/K to 2.3%/K. The magnitude of $1/f$ noise ($\alpha/N$) increases by more than an order of magnitude because the carrier concentration in the films decreases, enormously. However, the $\alpha$ seems to decrease owing to the increment of homogeneity in the films. For bolometer application it is desirable to increase the carrier concentration by decreasing the $C_2H_4/SiH_4$ at the cost of the $E_a$ which determines the TCR.

Table 1
Comparison of electrical properties of each sample with respect to $C_2H_4/SiH_4$

| Samples | $C_2H_4/SiH_4$[a] | $\sigma_d$@300 K ($(\Omega\,\text{cm})^{-1}$) | $E_a$ (meV) | TCR@300 K (%/K) | $K = \alpha/N$ | $D^{*}$[b] (cm Hz$^{1/2}$/W) |
|---|---|---|---|---|---|---|
| 1 | 0.07 | $6.80 \times 10^{-2}$ | 54.6 | 0.70 | $5.32 \times 10^{-12}$ | $1.78 \times 10^{8}$ |
| 2 | 0.20 | $1.54 \times 10^{-3}$ | 74.7 | 0.96 | $9.02 \times 10^{-11}$ | $8.05 \times 10^{7}$ |
| 3 | 0.33 | $5.13 \times 10^{-4}$ | 109.8 | 1.42 | $6.52 \times 10^{-11}$ | $1.39 \times 10^{8}$ |
| 4 | 0.47 | $1.24 \times 10^{-5}$ | 178.8 | 2.30 | $1.47 \times 10^{-10}$ | $1.53 \times 10^{8}$ |

[a] Process condition: substrate temperature = 250 °C, mercury bath temperature = 50 °C, $H_2/SiH_4 = 20$, $B_2H_6/SiH_4 = 3000$ ppm.

[b] Assumptions: bandwidth = 64 kHz, bias power = $1.89 \times 10^{-5}$ W, $G_{th} = 6.3 \times 10^{-7}$ W/K, $T = 300$ K, detector area = 50 μm × 50 μm, film thickness ≈ 230 nm.

## Acknowledgements

This work has been partially supported by the G7 project from Ministry of Industry and Energy and Ministry of Science and Technology of Korea, and partially supported by Micro Information and Communication Remote Object-oriented System (MICROS) Research Center at KAIST. The authors thank Chan-Hyung Park from Seoul National University for his advice in noise measurement.

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