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# Thermal Stability of $SiC_x$:H-Emitter Silicon HBTs

Mamoru Kuwagaki, Katsumi Murase, Kazuo Imai and Yoshihito Amemiya

NTT LSI Laboratories
3-1 Morinosato Wakamiya, Atsugi-shi, Kanagawa 243-01

Hydrogen evolution from $SiC_x$:H and $\mu$c-Si:H deposited by the plasma CVD method is studied by thermal desorption spectroscopy and IR spectroscopy. Influence of annealing at 450°C on the $h_{FE}$ of a $SiC_x$:H-emitter and a $\mu$c-Si:H-emitter HBT is also comparatively investigated. Part of hydrogen atoms in $SiC_x$:H are incorporated in a stabler manner than the hydrogen atoms in $\mu$c-Si:H. Accordingly, even after annealing at 450°C the $SiC_x$:H-emitter HBT exhibits a higher $h_{FE}$ than a homojunction transistor, while the $\mu$c-Si:H-emitter HBT does not show the wide-gap effect any longer.

## 1. INTRODUCTION

The silicon heterojunction bipolar transistor (Si-HBT) with a wide-bandgap emitter or a narrow-bandgap base is regarded as a key device to break through the operation-speed limitation of Si-LSIs composed of homojunction transistors[1,2]. In particular, the wide-bandgap emitter Si-HBT is attracting a growing interest because the conventional Si-LSI fabrication process can be employed with little alteration.

Among several materials proposed for the wide-bandgap emitter, hydrogenated microcrystalline Si ($\mu$c-Si:H) seems especially promising, having a low resistivity and a low interface-state density[3,4].

However, a number of problems must be overcome before $\mu$c-Si:H can be used in practical applications. The most serious problem is thermal instability. Hydrogen atoms in $\mu$c-Si:H easily evolve during thermal treatment at about 400°C which is required in the metallization and the packaging processes. This results in the generation of Si dangling bonds causing excessive base current, by which the wide-bandgap effect may be counteracted. Bandgap narrowing may also occur as a result of the hydrogen (H) evolution.

To overcome these problems, we have investigated the properties of plasma-CVD-deposited carbon(C)-doped $\mu$c-Si:H, hereafter referred to as $SiC_x$:H[5]. The expected effect of mixing $CH_4$ with the source gases is stabilization of incorporated H by C and/or by modifying the atomic configuration through modification of the plasma condition.

This paper describes the behavior of H in $SiC_x$:H during thermal treatment in comparison with that in $\mu$c-Si:H and the effect of annealing at 450°C on the current gain ($h_{FE}$) of a $SiC_x$:H-emitter and a $\mu$c-Si:H-emitter HBT.

## 2. EXPERIMENTAL

### 2.1 Film Preparation and Characterization

The source gases were a $SiH_4$-$H_2$-Ar mixture for $\mu$c-Si:H and a $SiH_4$-$CH_4$-$H_2$-Ar mixture for $SiC_x$:H. The deposition conditions are summarized in Table I. The C concentration in $SiC_x$:H determined by SIMS was $2\times10^{21}$ $cm^{-3}$.

Table I Deposition Conditions

| | |
|---|---|
| Substrate temperature: | 400° C |
| Deposition gas flow rate | |
| $SiH_4$: | 2.5 sccm |
| $CH_4$(only for $SiC_x$:H): | 0.8 sccm |
| Ar: | 50 sccm |
| $H_2$: | 150 sccm |
| RF power: | 0.26 W/cm$^2$ |

For characterizing the behavior of H in $SiC_x$:H and in $\mu$c-Si:H during annealing, H evolution was measured by thermal desorption spectroscopy (TDS)[6] and infrared (IR) absorption spectroscopy. The film thickness was 0.3 $\mu$m for TDS measurements and 5-6$\mu$m for IR measurements. Si wafers were used as the substrates. The temperature raising rate for TDS was 20 K/min.

The optical bandgap ($E_{opt}$) of $SiC_x$:H and $\mu$c-Si:H, before and after annealing in a $N_2$ ambient, was deduced from the photon energy dependence of the optical absorption coefficient in the visible light region. Quartz plates were used as substrates.

### 2.2 HBT fabrication

Si-HBTs were fabricated using n-type $SiC_x$:H or $\mu$c-Si:H as the emitter. For n-type doping, $PH_3$ was added at a rate of $4x10^{-3}$ sccm to the gas mixtures. The P concentration determined by SIMS was about $4x10^{20}$ cm$^{-3}$ in both $SiC_x$:H and $\mu$c-Si:H. Conventional Si planar technology, including boron ion implantation for the base-region formation, was employed in the transistor fabrication process before emitter formation. Details are described elsewhere[5]. The peak boron concentration in the base region was $1x10^{18}$ cm$^{-3}$. The emitter size was 10 $\mu$m x 1 $\mu$m.

A control homojunction transistor (homotransistor) was also fabricated. The emitter was formed by slightly diffusing As from As-implanted polysilicon. The base structure was essentially the same with the HBTs. The emitter carrier concentration was $1x10^{20}$ cm$^{-3}$.

## 3. RESULTS and DISCUSSIONS

### 3.1 Hydrogen Evolution

The H concentration in $SiC_x$:H determined by SIMS is $1x10^{22}$ cm$^{-3}$, and is 5 times as high as that in $\mu$c-Si:H ($2x10^{21}$ cm$^{-3}$).

The $SiC_x$:H and the $\mu$c-Si:H films exhibit different TDS H evolution spectra as shown in Fig.1. The evolution rate of H is expressed in terms of the Q-mass ion current at a mass number of 2. The H evolution spectrum of $\mu$c-Si:H has a single-peak pattern centered at 400° C. In contrast with this, $SiC_x$:H has two peaks centered at 400° C and 580° C, and shows incorporation of a thermal stabler component of hydrogen.

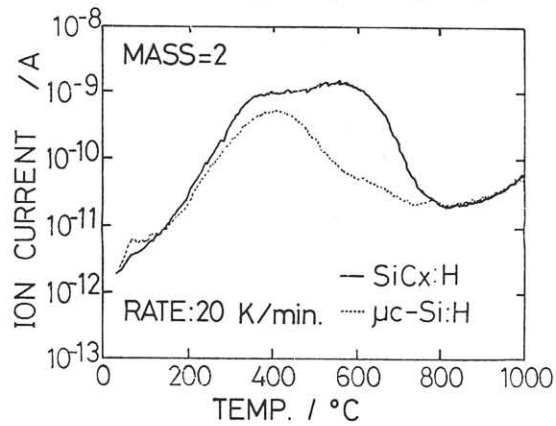


Fig.1. TDS H evolution spectra

Figure 2 shows IR absorption appearing in the wavenumber region from 1900 to 2200 cm$^{-1}$ due to the Si-H and the $Si-H_n$ (n>2)

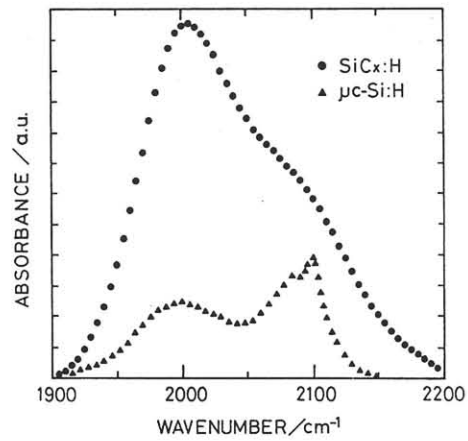


Fig.2. IR absorption spectra

stretching vibrations. Absorption by the C-H and the C-$H_n$ stretching vibrations in the range from 2800 to 3000 $cm^{-1}$ were not clearly observed due probably to a low C content and a small absorption cross section of the C-H stretching oscillators. As implied by the different H evolution spectra of $SiC_x$:H and $\mu$c-Si:H, their IR spectra are also quite different. The relative intensity of Si-H absorption with respect to Si-$H_n$ absorption is stronger in $SiC_x$:H than in $\mu$c-Si:H.

The H evolution during annealing at 450° C is shown in Fig. 3 as an annealing time dependence of the integrated absorption intensity $\int \alpha/k dk$, where $\alpha$ and k are the absorption coefficient and the wavenumber, respectively. The intensity is normalized by the as-deposited value. The integrated absorption intensity of Si-H in $SiC_x$:H decreases most slowly as the annealing proceeds. This stable component of H in $SiC_x$:H seems relevant to the high-temperature-side peak in the TDS spectrum of $SiC_x$:H.

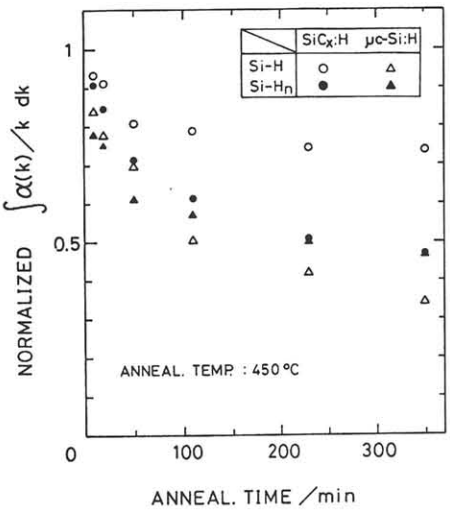


Fig.3. Integrated absorption intensity versus annealing time

All the results above indicate that part of H atoms are incorporated in $SiC_x$:H in a stabler manner than in $\mu$c-Si:H. The mechanism of H stabilization is still under investigation.

### 3.2 Optical Bandgap

Figure 4 shows $E_{opt}$ and B in the relationship $\alpha h\nu = B(h\nu - E_{opt})^2$ as a function of the annealing temperature, where $h\nu$ is the photon energy. The annealing time is 30 min.

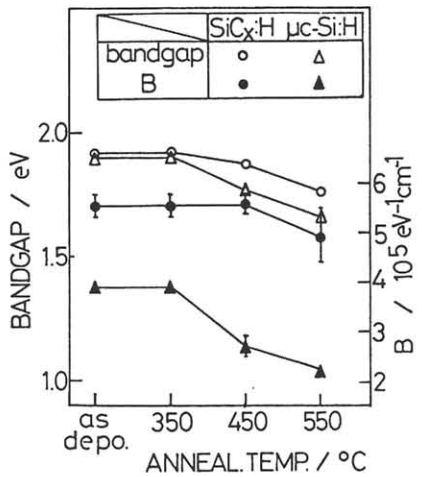


Fig.4. $E_{opt}$ and B of $SiC_x$:H and $\mu$c-Si:H versus annealing temperature

Above 350° C, $E_{opt}$ decreases with increasing temperature. However, even after annealing at 550° C, $E_{opt}$ is still large enough to exhibit the wide-gap effect in Si-HBTs, so long as generation-recombination centers do not increase. The value of B implies that the energy range of the tail states is narrower in $SiC_x$:H than in $\mu$c-Si:H. Moreover, the temperature dependence of B indicates that $SiC_x$:H is structurally stabler than $\mu$c-Si:H. This difference in the structural stability between $SiC_x$:H and $\mu$c-Si:H may somewhat reflect the difference in H incorporation described in 3.1.

### 3.3 HBT characteristics

The $h_{FE}$ versus collector current characteristics of the transistors are shown in Fig. 5. The effect of the wide-gap emitter is evident. The $h_{FE}$ values of both HBTs are much higher than that of the homotransistor.

The HBT characteristics after annealing in a $N_2$ ambient at 450° C for 30 min are shown in Fig. 6. Although the $SiC_x$:H-emitter HBT shows

a greater reduction in $h_{FE}$ at low collector currents than the $\mu$c-Si:H-emitter HBT, it maintains its maximum $h_{FE}$ well above that of the homotransistor, in contrast with the $\mu$c-Si:H-emitter HBT whose maximum $h_{FE}$ has dropped below that of the homotransistor. The reduction in $h_{FE}$ at low collector currents is most relevant to the deep gap-states, and that at high collector currents to the shallow gap-states or tail states. This is because the contribution of the deep gap-states to the recombination current becomes pronounced when the emitter-base junction is under a small forward-bias condition and therefore the energy level of the valence-band edge in the base is close to that of the deep gap-states in the emitter. When the emitter-base junction is deeply forward-biased, the tail states in turn mainly contribute to the recombination current. The density of the deep gap-states created as a result of H evolution is considered to be higher for $SiC_x$:H than for $\mu$c-Si:H, since the amount of H evolved during annealing, determined by SIMS, is $5\times10^{21}$ $cm^{-3}$ for $SiC_x$:H, and is 5 times as large as that for $\mu$c-Si:H. This is presumably responsible for the greater reduction in $h_{FE}$ at low collector currents of the $SiC_x$:H-emitter HBT. However, tail-states broadening by annealing is smaller for $SiC_x$:H than $\mu$c-Si:H as implied by Fig. 4. This is probably the background of

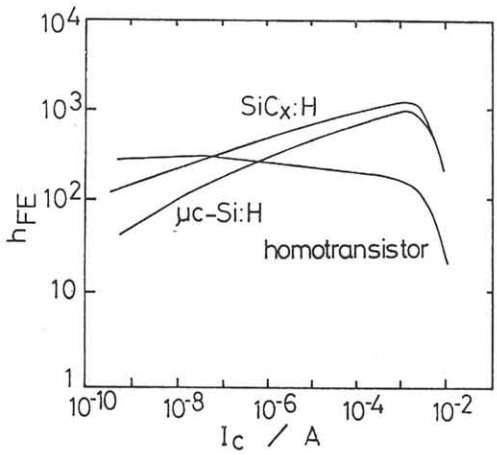


Fig.5. $h_{FE}$ versus collector current

the wide-gap effect maintained for the $SiC_x$:H-emitter HBT after annealing.

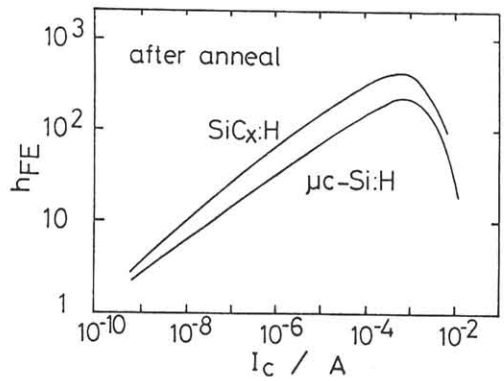


Fig.6. $h_{FE}$ versus collector current after annealing at 450° C

## 4. CONCLUSIONS

1) The $SiC_x$:H film contains a thermally stabler component of hydrogen than the $\mu$c-Si:H film.

2) The optical measurements indicate that $SiC_x$:H is structurally stabler against annealing than $\mu$c-Si:H.

3) The $SiC_x$:H-emitter HBT maintains higher $h_{FE}$ than the homotransistor even after annealing at 450° C, in contrast with the $\mu$c-Si:H-emitter HBT whose maximum $h_{FE}$ has dropped below that of the homotransistor.


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## REFERENCES


1) T. Sakai: Ext. Abst. 17th Conf. SSDM, 1985 p. 373.

2) M. Ugajin, S. Konaka, K. Yokoyama, Y. Amemiya: IEEE, Trans. Elect. Device, 36, (1989) p.1102

3) K. Sasaki, T. Fukazawa and S. Furukawa: Tech. Dig. IEDM, 1987 p. 186.

4) H. Fujioka, S. Ri and K. Takasaki: Tech. Dig. IEDM, 1987, p.190

5) M. Kuwagaki, K. Imai and K. Amemiya: Jpn. J. Appl. Phys. 28 (1989) L754.

6) P.A.Redhead: Vacuum, 12 (1962) p.203