

Wide-Bandgap μ c-Si:H/Single-Crystalline Si Abrupt Heterojunction by Si Surface Modification

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ABSTRACT

Structure of μ c-Si:H/c-Si heterojunction is investigated by temperature dependence of base current of HBTs and photocurrent response of Au/ μ c-Si:H SBDs on c-Si. μ c-Si:H deposited on a clean Si surface is crystallized in the vicinity of the heterojunction, consequently, bandgap energy of that portion is observed to be close to that of c-Si. Surface modification by a thin a-SiC:H layer suppresses the crystalline growth, resulting that wide bandgap μ c-Si:H/c-Si abrupt heterojunction is obtained so as to give good reproducibility.

1. INTRODUCTION

Hydrogenated amorphous Si based materials such as a-SiC:H and μ c-Si:H have been studied as hetero-emitter materials for Si-HBTs¹⁾. Among such materials, the μ c-Si:H is promising because of its low resistivity.

Recently, it has been made clear that crystalline Si (c-Si) sometimes tends to grow on a clean c-Si surface even under a μ c-Si:H film growth condition^{2), 3)}. Accordingly, abrupt heterojunction of μ c-Si:H/c-Si structure for possible use of Si-HBT can scarcely be obtained. And the bandgap energy of such μ c-Si:H films on c-Si substrates, especially in the vicinity of the heterointerface, is considered to be different from that measured on a glass substrate²⁾. Such unintentional crystallization will cause unreproducibility of device properties.

In this paper, we will discuss the structural model of such μ c-Si:H films by means of measuring both temperature dependence of device properties and an inner photoelectron effect. Then we will describe a surface modification method to obtain an abrupt heterojunction and its result.

2. EXPERIMENTS

μ c-Si:H films used were deposited using L-coupled plasma CVD apparatus by a method of Ar gas addition that we have developed. Details of deposition conditions are given elsewhere²⁾.

Using those films with heavily P doped as hetero-emitters, Si-HBTs were fabricated under different evacuation system. One is a turbo molecular pump and the other only a rotary pump. Temperature dependence of the base current was measured for each devices.

Furthermore, Au/ μ c-Si:H Schottky barrier diodes (SBD) on n⁺c-Si(111) substrate were fabricated for the various film thickness. In fabrication of the SBDs, lightly P doped μ c-Si:H films were used, and the thickness of Au was set as thin as around 10 nm so that the incident light penetrate through it without decay. Short circuit photocurrent spectra of the SBDs were measured.

Si surface modification was carried out by exposing to a plasma produced by SiH₄+CH₄+He mixture gases for a few tens second just before μ c-Si:H deposition. Photocurrent spectra were also measured to estimate the

modification effects with changing CH₄ fraction and thickness of a-SiC:H layer.

3. RESULTS AND DISCUSSION

3.1 HBT Properties

Device properties are summarized in Table 1 for the each devices denoted as HBT(A) and HBT(B).

The slope of the base current of HBT(A) tended to become steeper as the measuring temperature decreased and the base current property showed a exponential relationship of $\exp(qV/kT)$. This property suggests that the current is composed of the diffusion and recombination one. While, as for HBT(B), the slope of the base current was unchanged for temperature and the base current obeyed relationship of $\exp(\xi V)$, where ξ is the independent constant of temperature. This kind of current flow manner might be explained by the tunneling process. Furthermore, a difference is also observed in the current gain. HBT(B) shows higher current gain than that of HBT(A).

Table 1 Device properties summarized for each evacuation system used for μ c-Si:H film preparation.

	HBT(A)	HBT(B)
Evacuation System	Turbo Molecular Pump	Rotary Pump
Initial Vacuum	$\sim 10^{-6}$ Torr	$\sim 10^{-3}$ Torr
Base Current Properties	$\propto \exp(qV/nkT)$ Diffusion + Recombination Current	$\propto \exp(\xi V)$ Tunnel Current (ξ :Independent of T)
Current Gain	~ 100	300~500

In order to make clear the above phenomena, we have tried to estimate the bandgap energy of the hetero-emitter μ c-Si:H for HBT(A) by temperature dependence of the saturation base current assuming to obey the diffusion theory. However, we can not apply this method to HBT(B) since its base current is found not to obey the diffusion nor recombination theory.

The base current of HBT(A) is discriminated into the diffusion and recombination current, assuming that the diffusion current component has exponential relationship of $\exp(qV/kT)$ and recombination current component $\exp(qV/2kT)$. The derived saturation current I_{BDO} and I_{BRO} are plotted for $1/T$ as shown in Fig.1. If such assumption and discrimination method are reasonable, it is expected that temperature dependence of I_{BDO} is mainly governed by an intrinsic carrier concentration, consequently a bandgap energy in the emitter region.

As can be seen in this figure, the plots are well fitted on a line over 20 and 10 decades respectively. Besides, the bandgap energies derived from the diffusion and recombination current show almost the same value. Therefore, this method to determine bandgap energy is considered to be valid.

The derived value of 1.15 eV is much smaller than an optical bandgap energy of 1.75 eV which was measured by the sample on a glass substrate. These results suggest crystallization of μ c-Si:H in the case of a crystalline substrate. And crystallographical

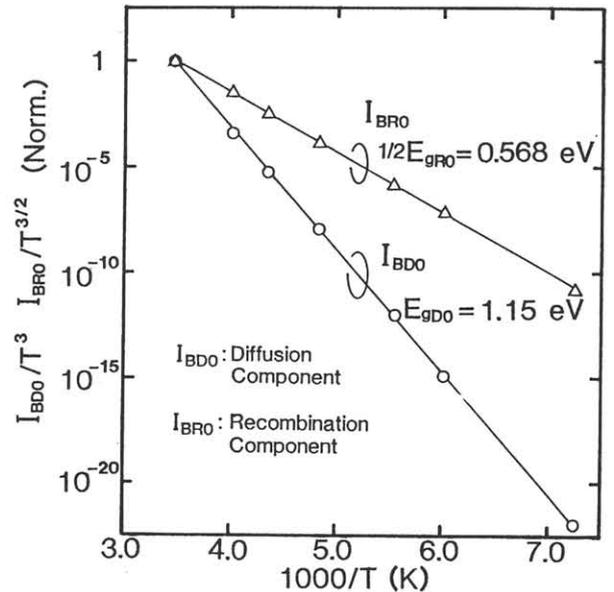


Fig. 1 Arrhenius plots of saturation current of the diffusion and recombination current component derived from the base current measured.

analysis²⁾ is consistent with such interpretation.

As for HBT(B), it is considered that unintentional surface contamination under not ultra-clean process might suppress crystalline growth. Therefore, μ c-Si:H having wide bandgap energy had grown to result in higher current gain. This interpretation might give one of the reasons why reproducibility of such type HBT having larger current gain is not good in many reports⁵⁾.

The above method for determining bandgap energy is useful. However, this method can not be applied when a bandgap energy of an emitter sufficiently larger than that of base. Under such situation, a reverse injected hole current becomes too small comparing with other excess currents to determine the emitter bandgap energy. Therefore, following alternative method has been studied.

3.2 Analysis of μ c-Si:H/c-Si Structure by Photoresponse

Bandgap energy of μ c-Si:H film is estimated by a method using the inner photoelectron effect instead of utilizing the activation energy of base saturation current.

Photocurrent spectra of Au/ μ c-Si:H/c-Si structure SBD are shown in Fig. 2. Also, the

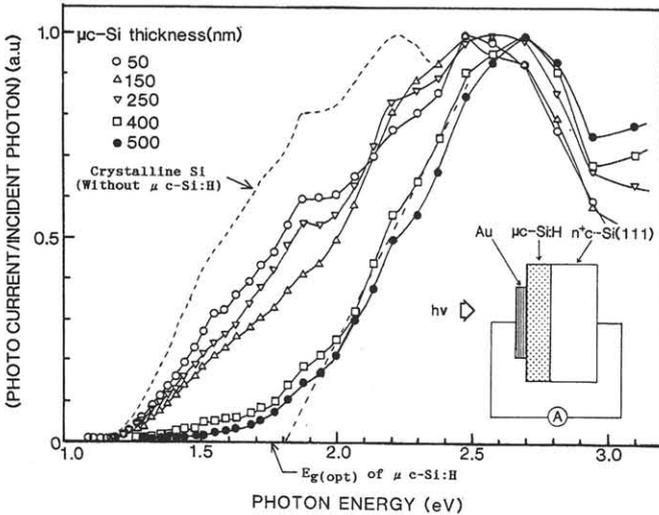


Fig. 2 Photoresponse properties of the short circuit current of the Au/ μ c-Si:H SBDs on n^+ c-Si(111) substrate.

spectra for c-Si are shown in the figure by dashed line as a reference. The threshold photon energy for c-Si is observed to be around 1.2eV, which is fairly good coincidence with the bandgap energy of c-Si. The samples with μ c-Si:H films having thinner thickness than 250 nm show the same threshold photon energy as c-Si. This means that those have the same bandgap energy, which consistent with the results of HBT(A). For the thicker films than 400 nm, the main photoresponse is seemed to shift to higher energy side, and the threshold energy determined by the main photoresponse agree with its optical bandgap energy measured by a sample on glass substrate. However, there is a tail region reaching to the threshold energy of c-Si in the photoresponse.

Those behavior could be explained by the structural model as shown in Fig. 3. If the μ c-Si:H films contain crystallized portions, which grow in pillar shape from the interface toward the surface, the crystallized portions would give the same photoresponse suggesting

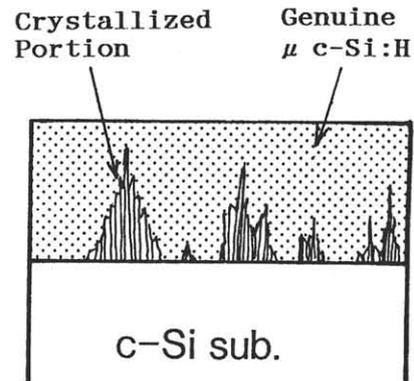


Fig. 3 The structural model for the μ c-Si:H/c-Si heterostructure.

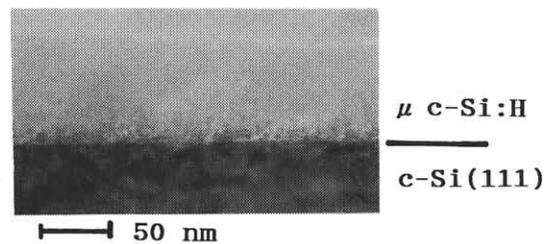


Fig. 4 Cross-sectional TEM image of the μ c-Si:H/c-Si heterostructure.

the same bandgap energy as c-Si. On the other hand, the other genuine μ c-Si:H portions would give the wide bandgap energy. In fact, such structural model shown in Fig.3 for the grown films on c-Si substrate has been confirmed as shown in TEM image of the μ c-Si:H/c-Si structure. (Fig.4)

3.3 Abrupt Heterojunction by Substrate Surface

Modification

A clean Si surface tends to initiate the homogeneous crystalline growth even at the low growth temperature. We have considered that an abrupt heterojunction could be obtained by suppressing such a crystalline growth at the Si clean surface. In order to do that, we examined to modify a c-Si surface by forming a very thin a-SiC:H layer on it. It is considered that the role of the modification is an amorphousization or inactivation of a Si surface by an a-SiC:H layer.

Photocurrent spectra for the sample on which is performed by the surface modification are shown in Fig.5. As can be seen in the figure, the photocurrent spectra respond sensitively to the condition of of the surface modification. In the case of the a-SiC:H layer thickness of around 2 nm and CH₄ fraction of 0.1 and 0.2, photocurrent starts flowing at

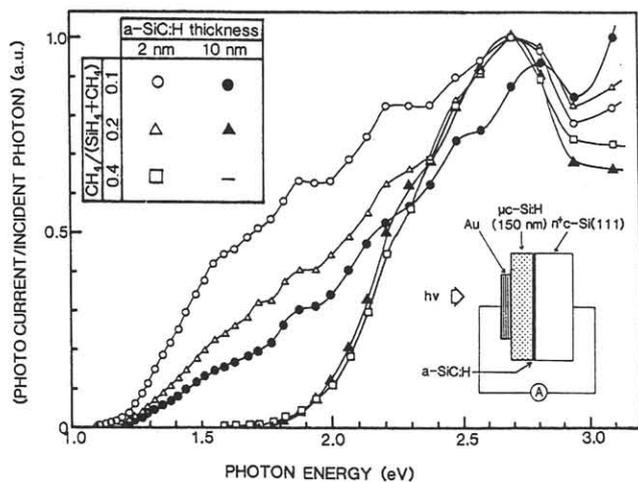


Fig. 5 Photoresponse properties of the SBDs applied the surface modification.

the same photon energy as c-Si, while photoresponse threshold energy obviously shifts to the higher energy of around 2.0 eV for CH₄ fraction of 0.4, even the thickness is as thin as 2 nm. These results mean that the surface amorphousization is complete for CH₄ fraction of 0.4, accordingly, an abrupt heterojunction is considered to be obtained. On the other hand, for the case of CH₄ fraction of 0.1 and 0.2, such surface modification to protect crystallization is not effective.

Furthermore, photoresponse is also affected by the thickness of the a-SiC:H layer. When the a-SiC:H layer thickness increases around 10 nm, the photoresponse shows the same threshold energy as that for CH₄ fraction of 0.4, even when CH₄ fraction is 0.2.

4. CONCLUSION

It is found that μ c-Si:H deposited on a c-Si substrate tends to be crystallized, so that such the emitter has the bandgap energy to be closed to that of c-Si. While, the crystallization is suppressed effectively by the substrate surface modification by a-SiC:H layer, resulting that an abrupt heterojunction is obtained. Such high sensitivity of the initial surface condition of the Si substrate (base region) for fabricating a μ c-Si:H emitter HBT can give an explanation that device properties reported have been fluctuated. It is concluded that the surface modification proposed is very useful to realize ideal HBT using μ c-Si:H as a hetero-emitter material.

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