Available online at www.sciencedirect.com
SCIENCE DIRECT®
Acta Materialia 54 (2006) 3227–3232
Acta MATERIALIA
www.actamat-journals.com

Solid–liquid interface energy of silicon

Zengyun Jian [a,*], Kazuhiko Kuribayashi [b], Wanqi Jie [c], Fange Chang [a]

[a] Department of Materials Science and Engineering, Xi'an Institute of Technology, Xi'an 710032, PR China
[b] Institute of Space and Astronautical Science, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan
[c] State Key Laboratory of Solidification Process, Northwestern Polytechnical University, Xi'an 710072, PR China

Received 18 February 2006; received in revised form 6 March 2006; accepted 9 March 2006
Available online 11 May 2006

Abstract

By examining the morphologies of the recalescence interface and the growing crystal, direct evidence for silicon to grow in intermediary mode has been found, and the critical undercooling for silicon from lateral growth to intermediary growth ΔT^* and that from intermediary growth to continuous growth ΔT^{**} have been determined. A method that predicts the solid–liquid interface energy on the basis of the critical growth transition undercooling has been developed. The solid–liquid interface energy predicted from ΔT^* for silicon is in very good agreement with that from ΔT^{**}. The percentage error between the solid and liquid interface energies predicted from ΔT^* and ΔT^{**} is smaller than 0.59% when the temperature is in the range 783–1683 K. The results obtained for the solid–liquid interface energy predicted from the critical growth transition undercoolings for silicon are also consistent with the reported results from the nucleation method and the grain boundary method. Their percentage errors are in the range 0.24–4.55%.

Keywords: Solid–liquid interface energy; Undercooling; Intermediary growth; Silicon

1. Introduction

The solid–liquid interface energy is an important physical parameter in research into solidification. It is impossible to comprehend the essences of nucleation and growth of crystals without a clear knowledge of the solid–liquid interface energy.

Direct measurements of the solid–liquid interface energy have been possible in opaque alloy systems [1–4] and transparent materials [4–6]. For opaque pure materials, it is difficult to measure directly the solid–liquid interface energy. These values have usually had to be extrapolated from the dependence of the solid–liquid interface energy of an alloy on composition, which can be measured using the grain boundary method [7] or estimated from the nucleation undercooling method on basis of the homogenous nucleation theory and the measured undercooling [8–11].

As is well known, the grain boundary method can only measure the solid–liquid interface energy at melting point, while the nucleation-undercooling method can only determine the solid–liquid interface energy at the undercooled state. Recently, Jian et al. [12] developed a model of the solid–liquid interface energy for lateral growth materials such as semiconductors. In terms of this model, the solid–liquid interface energy of a lateral growth material at any temperature can be determined if the critical growth transition undercooling is known. However, it is unclear whether the model corresponds to reality because the results of the model have not been reported.

Determination of the critical undercooling for a material to grow from lateral to intermediary mode or that from intermediary to continuous mode is crucial for applying the model developed by Jian et al. to predict the solid–liquid interface energy. It has been reported that the growth modes of silicon and germanium vary with increasing undercooling, and there are obvious different features when silicon and germanium grow in continuous mode and lateral mode [11,13–20]. However, direct evidence for

* Corresponding author. Tel.: +86 29 83208079; fax: +86 29 83208078.
E-mail address: jzycfe@pub.xaonline.com (Z. Jian).

1359-6454/$30.00
doi:10.1016/j.actamat.2006.03.009

a semiconductor growing in intermediary mode has not been reported.

The purpose of this paper, by examining the features for silicon growing in lateral, intermediary and continuous mode as well as the critical growth transition undercooling, is to introduce a useful method for determining the solid–liquid interface energy of lateral growth materials.

2. Experimental

Experiments to determine the critical undercooling for the growth transition of silicon were performed in an electromagnetic levitation facility that could be evacuated and filled with gases. The chamber of the electromagnetic levitation facility was firstly evacuated to 10^{-4} Pa using a turbomolecular pump and then filled with purified argon gas. A continuous-wave CO_2 laser was used to preheat a silicon sample of 99.999% purity so as to cause it to be levitated by an applied electromagnetic force. A high-speed camera was used to capture images of samples during the solidification process. The temperature was measured with a two-color pyrometer with 1 mm spot size. The spectral emissivity of silicon was determined in terms of the pyrometer temperatures measured at the solid–liquid coexistence.

3. Results and discussion

3.1. Critical undercooling for the growth transition of silicon

The growth mode of silicon can be predicted according to the morphologies of the recalescence interface and the growing crystal during the solidification process. Figs. 1–3 show the morphologies of the recalescence interface and the growing crystal during the solidification process as observed with the high-speed camera. The dark, gray and bright parts in the figures are the undercooled liquid, the reheated liquid resulting from the release of latent heat and the solid that has solidified from the liquid, respectively. When the undercooling is less than 100 K, as shown in Fig. 1(a), the crystal can be detected during the recalescence process. The initial image of the crystal, as shown in Fig. 1(a) and (b), is a discontinuous line or several discontinuous lines. As time goes on, as shown in Fig. 1(c), the discontinuous lines develop into continuous strips. This

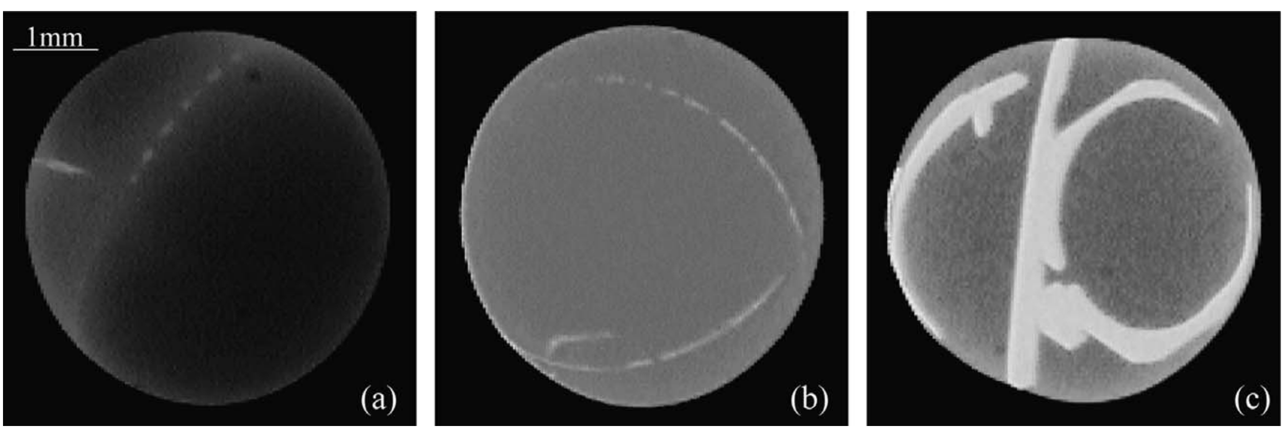

Fig. 1. Surface morphology of silicon with undercooling of 52 K observed with a high-speed camera: (a) $\tau = 2$ ms, (b) $\tau = 8$ ms and (c) $\tau = 1040$ ms (where τ is the time after nucleation takes place).

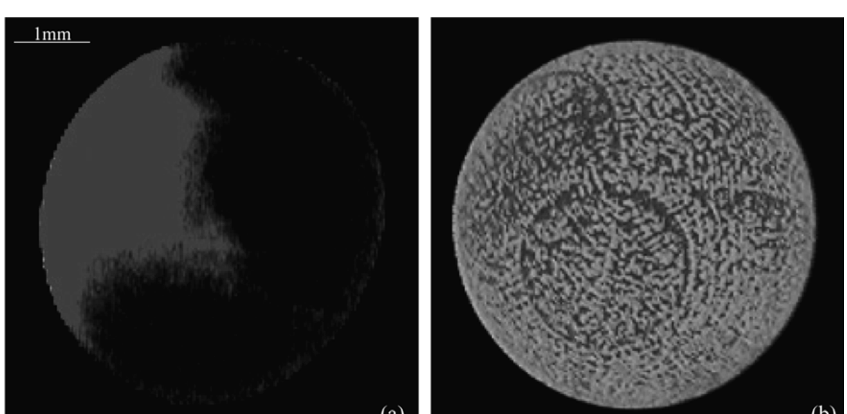

Fig. 2. Surface morphology of silicon with undercooling of 152 K observed with a high-speed camera: (a) $\tau = 0$ ms and (b) $\tau = 372$ ms (where τ is the time after nucleation takes place).