Ultrasonics 54 (2014) 731–736

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

Leap behavior of ultrasonic standing waves in the liquids

G.N. Kozhemyakin [*]

Department of Micro- and Nanoelectronics, Volodumur Dahl East Ukrainian National University, Bl. Molodezhniy, 20 A, 91034 Lugansk, Ukraine

ARTICLE INFO

Article history:
Received 14 April 2013
Received in revised form 17 September 2013
Accepted 20 September 2013
Available online 2 October 2013

Keywords:
Standing wave channel
Half wavelength
Antinodes
Fluids
Crystal growth

ABSTRACT

The generation and behavior of ultrasonic standing waves was modeled using the light cut method for transparent fluid. The oscillations of the fluid surface in initial moment of switching on ultrasound and appearance of standing wave channel were observed. The effect of continuous fluid depth decrease and increase on the behavior of ultrasonic standing wave channel was studied. The ultrasonic standing wave channel floated in the liquid between of the crucible bottom and fluid surface and discretely changed its height by half ultrasonic wavelength with the decrease or increase of the liquid level. This channel had the behavior of a “quasi solid state” and damped of convection.

1. Introduction

Dopant inhomogeneity is common in single crystals grown by various crystallization methods [1,2]. One type of inhomogeneity is growth striations, which considerably impair electrophysical properties of semiconductor single crystals and are especially undesirable for nanocrystals growth on substrates. The growth striations appear in crystals during the growth process as a result of temperature fluctuations at the interface, brought about by convection currents in the melt. This inhomogeneity was investigated in detail in InSb single crystals [3,4]. It should be noted that the external fields, such as gravitational, magnetic, and ultrasonic fields can influence the growth process and control the striations.

Various research groups have studied the crystallization under zero gravity [5–8]. On the other hand, the growth process in a centrifuge with increased gravity was investigated [9]. A modified vertical Bridgman method with the baffle in the melt also makes it possible to damp the natural convection in the melt during growth and results in homogeneous distribution of components [10].

It has been shown by many investigators that magnetic fields can suppress natural convection in the melts [11–16]. However, these methods are very complex and expensive for industrial applications.

The ultrasound can also be used to eliminate the growth striations in semiconductor single crystals [17,18]. The first application of vibrations at frequencies of 50 and 100 Hz introduced into the melt showed that it can serve as a unique tool to learn about the distribution of impurities during crystal growth [19]. Detailed investigations of the effect of ultrasonic vibrations with a frequency of 10 kHz and power from 30 to 150 W on the growth morphology in InSb and $In_xGa_{1-x}Sb$ single crystals were conducted by Hayakawa et al. [20–23]. The introduction of ultrasonic vibrations into the melt through the bottom of a carbon crucible during the growth process changed the crystal diameter, the width of the facet region and appearance of large voids with an increase of the output power to 150 W. On the other hand, a certain periodicity of the component distribution was found during the crystal growth in water and Seignette’s salt in ultrasound at a frequency of 51.5 MHz [24].

Our group has been investigating the influence of ultrasonic waves introduced into melts at frequencies from 0.15 to 10 MHz on the growth process of semiconductor single crystals for over 30 years. We studied the growth process of GaAs, InSb, $Ga_xIn_{1-x}Sb$ and Bi_xSb_{1-x} solid solution single crystals and the influence of ultrasonic field on striations [18,25–27]. We showed that the ultrasound can dampen convection due to formation of standing waves, and therefore, the component inhomogeneity in grown single crystals decreases. These conditions were confirmed in model experiments with transparent fluids [28,29].

Application of a high frequency ultrasound can generate a standing wave channel in the melt between the solid–liquid interface and the waveguide. It is known that the distance between the emitter and reflector must be multiple of half of the wavelength for generation of the standing waves. It is difficult to ensure the constant melt depth during the crystal growth process. Additionally, the crystal growth by Czochralski method characterizes the decrease of the melt depth. Ordinarily a mass of pulled crystal in

---

[*] Tel.: +380 507622020; fax: +380 642413160.
E-mail address: genakozhemyakin@mail.ru

0041-624X/$ - see front matter
http://dx.doi.org/10.1016/j.ultras.2013.09.021

Czochralski growth constitutes from 10% to 60% of a mass melt. Therefore, the melt depth can decrease from a one mm to next decade's mm. However, the results of ultrasonic effect on the component inhomogeneity in pulled crystals indicate that standing waves kept permanently during the growth process [27]. A model experiment with evaporating acetone showed that the standing wave channel did not disappear after the fluid decrease by 4 mm [29]. However, our previous experiments did not illustrate the standing wave behavior during a continuous decrease of the fluid level all the way to the crucible bottom. Additionally, detail the study of standing wave influence on the fluids creates possibilities for fundamental investigations in another field of science and nanotechnological applications.

The present study focuses on the mechanism of appearing and behavior of ultrasonic standing waves in the fluids and melts for Czochralski crystal growth process in the conditions for the permanent change of the distance along standing wave direction.

2. Experimental

2.1. Method

Phenomena of the generation and behavior of ultrasonic standing waves for the Czochralski growth was modeled using the light cut method with transparent fluids. It is known that favorable conditions for the growth of single crystals are determined by the steady-state convection. Moreover, we established earlier that ultrasonic standing waves appear in the melts only at steady-state convection [28,29]. Therefore, we selected a transparent liquid, geometry, and temperature conditions to match the Rayleigh number to that of the semiconductor melts of interest.

The Rayleigh number for insulated walls of the crucible Ra_w is defined as [30]:

$$\mathrm{Ra}_w = g\alpha 2\Delta T_r h^4/\chi\nu d, \tag{1}$$

where g is the gravitational acceleration, α is the volumetric thermal expansion coefficient, ΔT_r is the radial temperature difference in the fluid, h is the height of the fluid, d is the diameter of the crucible, χ is the thermal diffusivity and ν is the kinematic viscosity.

The properties and experimental parameters of liquids and melts are given in Table 1. Distilled water had the maximal Ra_w at the given experimental parameters and closer to the conditions of non-stationary convection, which occurs during the growth of large crystals. Water is closest to the kinematic viscosity melts and the density to buoyant tracer particles. This may reveal some features of the standing waves which are difficult to be estimated in other transparent liquids. Therefore, distilled water was used as model fluid. Water was contained in an ebonite crucible with 30-mm inner diameter, 40-mm outer diameter, 30-mm height, with two glass windows for light beam and flow observation (Fig. 1). A foam plastic disk with 16-mm diameter and 10-mm thickness floating on water surface served as a dummy crystal. A needle with plastic tube was used for decant the distilled water from the crucible into a glass, which was attached below the crucible. Due to this, the depth water decreased slowly and created the illusion of the melt decrease during pulling of a crystal.

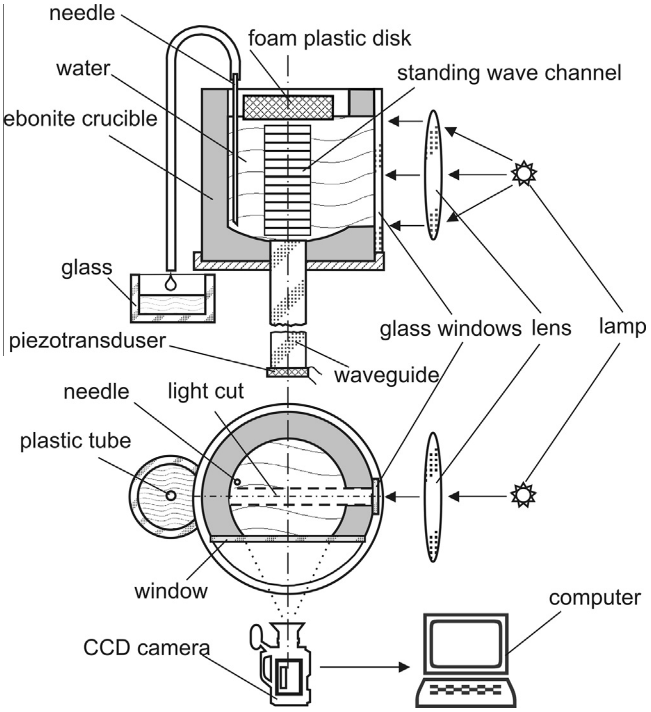

Fig. 1. Schematic representation of the light-cut technique for the observation of ultrasonic standing waves in transparent fluids.

2.2. Ultrasound parameters and materials

Ultrasound at a frequency 0.69 MHz was introduced into the water from a piezotransducer through the crucible bottom and a quartz waveguide of 10-mm diameter and 90-mm length. The direction of ultrasonic waves was parallel to the crucible axis. Buoyant tracer particles of textolite with the density of 1270 kg/m^3 had 50-μm diameter were suspended in distilled water.

2.3. Characterization

A CCD camera was installed such that ultrasonic standing waves in water could be viewed and recorded on video. The influence of the water depth decrease on standing waves behavior was observed between a dummy crystal and the waveguide using digital image processing software Ulead Video Studio 10 plus. Ultrasonic standing waves were recorded in video clips, which can be viewed on TV and PC in AVI (720 × 480, 29.97 fps, DV NTSC) format. The

Table 1
Properties and parameters of melts and transparent liquids.

Constants and numbers	Bi–Sb	In–Sb	GaAs	H_2O	H_2O: $C_3H_8O_3$10%: 90%	Acetone
Gravity, g (m/s^2)	9.8	9.8	9.8	9.8	9.8	9.8
Thermal coefficient of volume expansion, α (K^{-1})	1.5×10^{-4}	5.2×10^{-5}	1.87×10^{-4}	2×10^{-4}	0.4745×10^{-3}	1×10^{-3}
Radial temperature difference in fluid, ΔT_r (K)	4	4	9	4	4	4
Height of fluid, h (m)	0.023	0.023	0.03	0.023	0.023	0.023
Thermal diffusivity, χ (m^2/s)	0.85×10^{-5}	1.04×10^{-5}	0.7×10^{-5}	0.015×10^{-5}	0.103×10^{-6}	9.27×10^{-5}
Kinematic viscosity, ν (m^2/s)	13.1×10^{-6}	0.34×10^{-6}	0.488×10^{-6}	1×10^{-6}	4.39×10^{-4}	9.7×10^{-9}
Diameter of crucible, d (m)	0.04	0.04	0.09	0.03	0.03	0.03
Rayleigh number (Ra_w)	7.4×10^2	8.1×10^4	8.7×10^4	9.6×10^5	7.7×10^3	8.1×10^5