Ultrasonics 61 (2015) 33–39

Contents lists available at ScienceDirect

Ultrasonics

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

Influence of temperature on ultrasound absorption in waveguides made out of refractory materials

G.N. Kozhemyakin *, A.A. Bulankina

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

ARTICLE INFO

Article history:
Received 5 July 2014
Received in revised form 26 February 2015
Accepted 28 February 2015
Available online 7 March 2015

Keywords:
Waveguides
Buffer rods
Crystal growth
Ultrasound absorption
Ultrasound intensity

ABSTRACT

We studied the influence of temperature increase to 1500 °C on ultrasound absorption at frequencies from 0.1 to 1.0 MHz in tungsten, molybdenum, vanadium, graphite, and fused silica. The ultrasound absorption coefficient in these materials was calculated. It was shown that the fused silica has the smallest ultrasound absorption coefficient for temperatures up to 1000 °C. Vanadium and graphite also have small values of this coefficient for the considered temperature. The ultrasound absorption was investigated experimentally in graphite and fused silica waveguides. We demonstrated that the ultrasound absorption did not change in graphite with the temperature increase, but it increased in fused silica by a factor 2 for the temperature above 1000 °C. We show that different acoustical and mechanical properties of vanadium, graphite, and fused silica allow using them for waveguide applications and buffer rods in crystal growth at temperatures below 1500 °C and ultrasound frequency below 1.0 MHz.

1. Introduction

Bulk crystal growth methods often have a problem of composition inhomogeneity [1]. Dopant inhomogeneity impacts electrophysical properties of semiconductor single crystals [2,3]. Growth striations are a hardly removable inhomogeneity in semiconductor crystals [4]. Silicon single crystals are the main semiconductor material used in electronics [5–7]. Growth striations in silicon substrates degrade electrophysical parameters of semiconductor nanostructures in integrated chips. It is theoretically proven and experimentally shown that the striations in single crystals are formed by convective flow in the melt [8]. Therefore, suppression of convection during crystal growth prevents the appearance of striations.

The effect of ultrasound on semiconductor crystal growth decreases the component inhomogeneity [9–11]. Moreover, ultrasound at a high frequency creates favorable growth conditions for single crystals without dopant striations [12–15]. In this method, ultrasonic waves are introduced into the melt through a waveguide during crystal growth process. Ultrasonic energy dissipates in the waveguide, melt, and on the boundaries between a piezo transducer, waveguide, crucible, and melt during wave propagation from a piezo transducer to the solid–liquid interface of a growing crystal. The sound absorption coefficient is an important parameter defining the effect of ultrasound on the substance. This coefficient was determined for some semiconductor melts, and has a very small value [13]. Ultrasonic waves pass the greatest distance in the waveguide during crystal growth process. The waveguide temperature can change along its axis from 50 °C in a piezo transducer to 1500 °C in the melt for typical growth conditions of the single crystals. The temperature can considerably change acoustical and mechanical properties of the waveguide materials. These properties define the applicability of chosen materials for waveguides in crystal growth for the purpose of introduction of ultrasound into melts and other applications. Therefore, our analysis of ultrasonic energy dissipation in waveguides and buffer rods for temperatures up to 1500 °C has a scientific and practical interest.

In this paper, we present the results of an investigation of ultrasound absorption in waveguides at high temperature and frequency.

2. Material and methods

Ideally, the acoustical and mechanical properties of waveguides should not vary with temperature and frequency for ultrasound introduction into the melt at high temperature. Such materials can be refractory metals and some non-crystalline materials. Therefore, we selected the following materials for our investigations: tungsten (W), molybdenum (Mo), vanadium (V), graphite and fused silica. We considered these metals as polycrystals for

* Corresponding author.
E-mail address: genakozhemyakin@mail.ru (G.N. Kozhemyakin).

http://dx.doi.org/10.1016/j.ultras.2015.02.021
0041-624X/

the calculation of their ultrasound absorption coefficient. Graphite also has crystal structure, but high purity graphite used in crystal growth has porosity. Fused silica is an amorphous material and has no crystalline structure. It is possible polycrystallinity of graphite and non-crystallinity of fused silica will not allow obtaining reliable calculation data of the sound absorption coefficient. Therefore, we developed a setup for the ultrasound absorption measurement in graphite and fused silica at high temperatures (Fig. 1). It should be noted that the waveguides made out of these materials had 300 mm length and were heated only at one end for the introduction of ultrasonic waves into melts contained in a Czochralski crucible during the crystal growth process [13]. The quartz waveguide had 15 mm diameter and 500 mm length. Two graphite waveguides with 30 mm diameter and 300 mm length were firmly pressed at end faces, making the total length of the waveguide equal to 600 mm. These waveguides were fixed in a cylindrical heater. Two piezo transducers were attached to the waveguide end faces and were used as a source and receiver of ultrasound. The central region of the waveguide was heated using a cylindrical heater with 35 mm inner diameter and 50 mm length. The temperature was measured on the lateral surface of the waveguides with a *K*-type thermocouple inside of the heater. Such laboratory setup provided the temperature increase from 20 °C to 1300 °C in the central region of the waveguide to maintain the temperature of piezo transducers near 60 °C.

3. Theory/calculation

The melting points of the investigated materials, which were considered for the application as waveguides, are above 1500 °C, and have the following values: W – 3410 °C, Mo – 2617 °C, V – 1890 °C, graphite – 3750 °C, and fused silica ~1665 °C [16,17]. An ultrasonic wave loses a part of its energy for distribution in the waveguide. This dissipated energy is characterized by the ultrasound absorption coefficient α, which was calculated for investigated metals according to the following equation [18]:

$$\alpha = \frac{\omega^2}{2\rho\upsilon_\ell^3}\left[\left(\frac{4}{3}\eta + \xi\right) + \frac{kT\beta^2\rho^2\upsilon_\ell^2}{C_p^2}\left(1 - \frac{4}{3}\frac{\upsilon_t^2}{\upsilon_\ell^2}\right)^2\right], \quad (1)$$

where $\omega = 2\pi f$ is the circular frequency, f is the frequency, ρ is the density of the metal, k is the thermal conductivity, β is the coefficient of thermal expansion, η is the shear viscosity, ξ is the volume viscosity, υ_ℓ is the longitudinal velocity of an ultrasonic wave, υ_t is the shear velocity of an ultrasonic wave, C_p is the specific heat capacity at constant pressure, T is the temperature of the metal. Ultrasonic wave absorption in solids is defined by the internal friction and heat conductivity, which in this equation are the first and second terms, respectively [18].

The longitudinal velocity of ultrasonic waves in the metals defined by

$$\upsilon_\ell = \sqrt{\frac{E}{\rho}} \cdot \sqrt{\frac{1-\sigma}{1+\sigma} \cdot \frac{1}{1-2\sigma}}, \quad (2)$$

where E is the Young's modulus, σ is the Poisson's coefficient.

The Poisson's coefficient is calculated by:

$$G = \frac{E}{2(1+\sigma)}, \quad (3)$$

where G is the shear modulus.

The shear velocity of an ultrasonic wave in the waveguides is defined by:

$$\upsilon_t = \sqrt{\frac{E}{\rho}} \cdot \sqrt{\frac{1}{2(1+\sigma)}}. \quad (4)$$

The parameters for calculation of the ultrasound absorption coefficient are listed in Table 1 [16,17].

The ultrasound absorption in the waveguide decreases the ultrasound intensity I according to the equation [19]

$$I = I_0 \cdot e^{-2\alpha x}, \quad (5)$$

where $I_0 = P/S$ is the ultrasound intensity introduced into the waveguide, P is the ultrasound power introduced into the waveguide, S is the waveguide cross section area, and x is the waveguide length.

4. Results and discussion

The calculation results for the ultrasound absorption coefficient for the metals at frequencies of 0.1, 0.5 and 1.0 MHz, graphite and fused silica at frequencies of 0.72 MHz and 0.83 MHz, respectively, are submitted in Table 2. All studied metals have a high ultrasound absorption coefficient, which increases nonlinearly with the increase of temperature to 1500 °C and ultrasound frequency to 1.0 MHz. Tungsten has the highest value of the ultrasound absorption coefficient, which increases even at a frequency of 0.1 MHz from 11.3 m^{-1} to 75 m^{-1} with the temperature increase. This coefficient in tungsten is higher due to its high thermal conductivity and low specific heat capacity. Additionally, tungsten has a high density, and it is difficult to produce waveguides from it. The ultrasound absorption coefficient in molybdenum also has large values and increases from 1.5 to 6.2 m^{-1} with the temperature increase at a frequency of 0.1 MHz. Vanadium has the lowest ultrasound absorption coefficient from the considered metals. Its coefficient has a value around 1 m^{-1} at a frequency of 0.1 MHz and rises with the temperature increase only by a factor of 3. In our application, a waveguide should have good acoustical and mechanical properties for loads over 200 kg of the melt in crystal growth conditions. The mechanical properties of vanadium degrade by 30% at high temperature, as it has a lower melting point of only 1890 °C. Therefore, vanadium waveguides can be used with insignificant

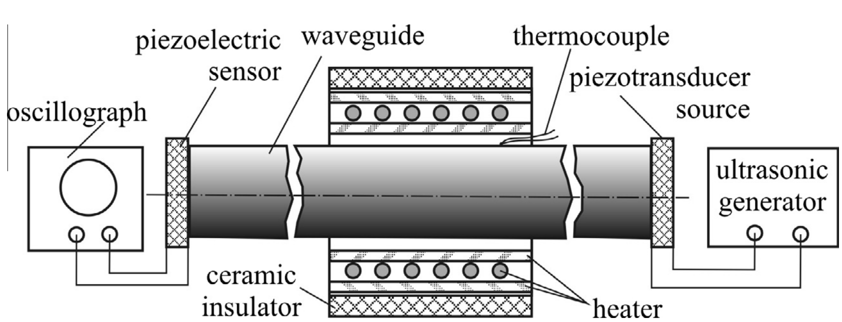

Fig. 1. Schematic drawing of the setup for ultrasound absorption measurement.