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Neurosurgery contact handheld probe based on sapphire shaped crystal

I.A. Shikunova [a], D.O. Stryukov [a], S.N. Rossolenko [a], A.M. Kiselev [b], V.N. Kurlov [a,*]

[a] *Institute of Solid State Physics Russian Academy of Sciences, Academician Ossipyan str. 2, 142432 Chernogolovka, Russia*
[b] *Moscow Regional Research Clinical Institute, Schepkina str. 61/2, 129110 Moscow, Russia*

A R T I C L E I N F O

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A B S T R A C T

A handheld contact probe based on sapphire shaped crystal is developed for intraoperative spectrally-resolved optical diagnostics, laser coagulation and aspiration of malignant brain tissue. The technology was integrated into the neurosurgical workflow for intraoperative real-time identification and removing of invasive brain cancer.

1. Introduction

Sapphire has a high refractive index and a broad transmission band spanning the ultraviolet, visible and infrared bands, a high hardness and melting point, very good thermal conductivity, tensile strength and thermal shock resistance [1]. However, sapphire is difficult to shape because of its high hardness, and its anisotropic physical properties since it possesses a hexagonal crystal structure. To solve these problems various techniques to grow sapphire crystals of any predetermined cross-section, constant along the crystal length, and crystals with discretely changing cross-sectional configurations have been developed [2] based on the EFG (edge-defined film-fed growth) [3] or Stepanov [4] methods.

The favorable combination of excellent optical and mechanical properties, along with high chemical inertness, resistance to human blood and body fluids makes sapphire an attractive structural material for medical applications. Over the last few years new medical instruments and devices for laser photodynamic and thermal therapy, laser surgery, fluorescent diagnostics, and cryosurgery based on sapphire crystals of various shapes with capillary channels in their volume have been developed [5–9].

The aim of this work is to create the neurosurgical handeld contact probe based on a sapphire multi-channel crystal for brain tumors' resection with demarcation of borders of a tumor by spectrally-resolved diagnostics with simultaneous coagulation and aspiration.

Specific tissue identification during a brain surgery is very essential to ensure patient safety and maximize tissue preservation. Because of the difficulty and often the impossibility to visually distinguish the infiltrated growing primary brain cancer from normal brain, the invasive brain cancer cells frequently remain after surgery, leading to disease recurrence. The goal of surgical resection of brain tumors is to maximize the extent of tumor removal, which correlates directly with improved patient survival and quality of life.

Various optical diagnosis principals are used to solve the problem of intraoperative demarcation from healthy tissue to tumor. Among them are the brain cancer detection with Raman spectroscopy [10,11], detection of brain cancer infiltration using quantitative optical coherence tomography [12], fluorescence imaging with autofluorescence [13,14] and fluorescent diagnostics with photosensitizers [15,16].

Nowadays, the most common intraoperative visual fluorescence imaging has emerged as a promising tool to aid the surgical guidance, but does not fully exploit the potential of the fluorescent agents and leads to missing the visually undetectable tumor sites. In general, besides the subjective assessments of the visible fluorescence the surgeons need the precise local measurements on the base of spectrophotometry. Point spectrometric probes allow both the perfect distinction between tumor and healthy tissue and the opportunity of measurement by imbedded probe to deepen the penetration of diagnosis. To enhance the accuracy one can use the indexes' set analysis, simultaneously recorded by optical channel (combined spectroscopy): the indexes of blood volume, hemoglobin oxygen saturation, protoporphyrin PpIX accumulation, and change in the scattering properties [17,18]. Contact fiber optic probes are favorable for spectrally-resolved optical diagnostics, but they are difficult to sterilize. Additionally the employment of separated instruments for diagnostics, localized

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[*] Corresponding author.
E-mail address: kurlov@issp.ac.ru (V.N. Kurlov).

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hemostasis and removing of diagnosed tumor tissues remains the impediment that can lead to mistakes and raise the risk of both tumor fragments missing or accidental removal of healthy tissue.

To address these problems, we developed a handheld contact neurosurgical transparent sapphire probe which combines in one surgical tool the spectral resolved diagnostics of brain tissue state and the opportunity of tumor removal by aspiration through open-ended channel of sapphire probe [19]. Any type of phototherapy such as photodynamic therapy and laser coagulation of tissues and blood vessels can be fulfilled directly on any stage of the operation.

2. Growth of multichannel sapphire shaped crystal

A solution of technically complex problem to form and maintain channels geometry during the EFG/Stepanov growth process was successfully fulfilled by both optimization of growth velocities and temperature modes and new approaches to die design and system of crystallization front state control.

The scheme of growth from the melt of sapphire rod with three channels for neurosurgical probe is shown on Fig. 1. The sapphire shaped crystals were grown in a 22 kHz induction heated graphite susceptor/molybdenum crucible setup held within a growth chamber. The crystal is grown from a melt film formed on the top of a capillary die. The melt rises to the crystallization front through the 0.2-0.3 mm wide ring capillary channel. The relative position of the die top with respect to the radiation shielding was an experimental variable, affecting the temperature gradient at the solidification interface. The cross-section of sapphire multichannel rod is mainly controlled by the die design, and its cross-sectional dimensions can vary only within very narrow limits restricted by the meniscus-existence zone, with the melt meniscus catching on the die free edge. Pulling rate was 60–80 mm/h. A high purity Ar atmosphere was used as an ambient under a pressure of 1.1–1.3 atm. *C*-axis sapphire seeds were used to initiate the crystal growth. The feed material was crushed Verneuil crystals.

Discrete variation of the crystal cross-section geometry (the transition from the channels to the monolithic part) during growth was based on the relative displacement of the thermal zone elements in a vertical plane [20,21]. In order to change the preset crystal shape during crystallization and to preserve the altered cross-sectional configuration during further growth, it is necessary to alter the geometry of the liquid meniscus. This technique consists of a sequence of steady state growth steps with different transition crystallization modes. During the transition the meniscus base moves across the top surface of the die assembly from one edge to the other, and the meniscus volume and shape are changed. The set of dies is not connected with the crucible. So, the crucible can be translated along the vertical axis relative to a fixed position of the die assembly. The parts of the die have different lengths to allow their lower parts to be dipped into the melt separately. To realize the shape transition mode the lateral surfaces of the neighboring dies are separated by narrow gaps which can serve as capillary feeding channels for the melt. When the crucible is raised so that the next die is dipped into the melt, the capillary gap supplies an additional mass of melt to the top of the die assembly. This portion of the melt contacts the already existing meniscus with the edge of the die just dipped into the melt. As a result, a new type of meniscus forms and the growing crystal alters its shape which is controlled by the dies dipped into the liquid, Fig. 1 (at the left).

Automated control system (ACS) for the growth process of the multichannel crystal rod is based on the use of crystal weight sensor. Action of ACS in a course of crystal growth includes 4 different stages: (1) crystal enlargement of the crystal after seeding, (2) stationary growth of the multichannel crystal rod, (3) process of closing some channels, (4) stationary growth of the rod with several closed channels.

The observation equation should be written for each crystal growth stage. It is necessary for producing the program weight

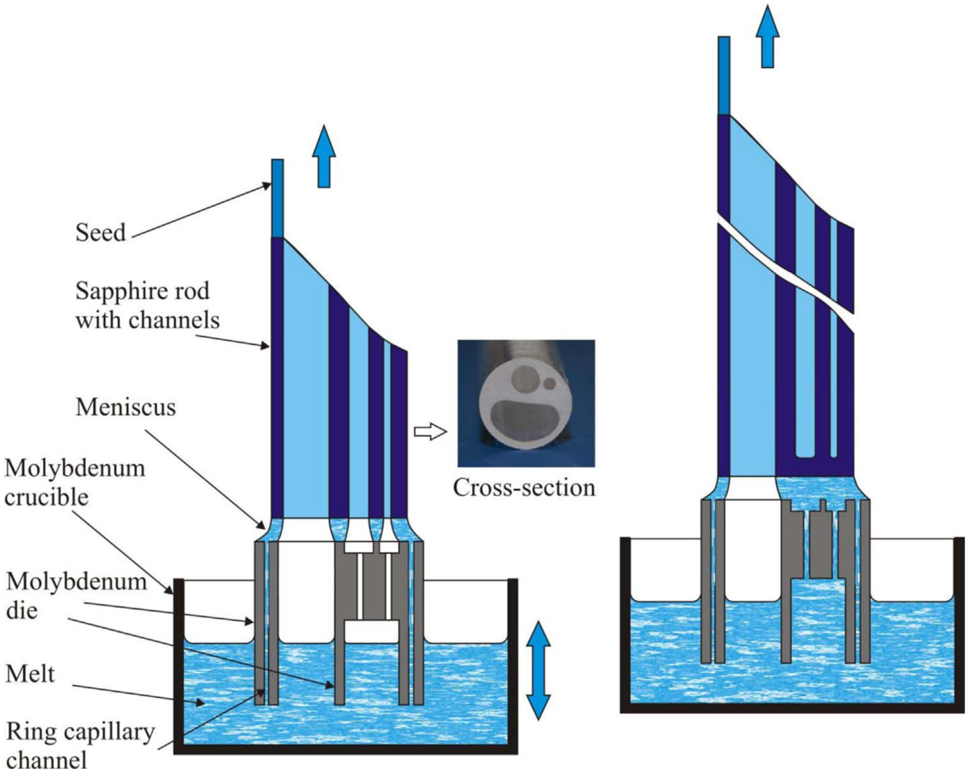

Fig. 1. A scheme of growth of sapphire multi-channel rod with discretely changing cross-section configuration: at the left – sapphire rod with three channels; at the right – sapphire rod with one channel.