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Thermal conductivity of hybrid SiC/Si substrates for the growth of LED heterostructures

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The thermal characteristics of SiC/Si samples obtained by the method of coordinated substitution of atoms at different thicknesses of SiC have been experimentally investigated. It has been found that for SiC thicknesses less than 200 nm, the thermal resistance of SiC/Si is approximately equal to 2 K/W, which is the same as for pure silicon substrate. Such samples will perfectly remove heat from the light-emitting heterostructure grown on SiC/Si. With an increase in the thickness of SiC, the SiC film is detached, which leads to a loss of thermal contact between SiC and Si. The thermal resistance increases at the same time by more than two orders of magnitude. The ability to remove easily the opaque part of the substrate can form the basis of the technology for manufacturing flip-chip LED.

Keywords: LEDs, silicon carbide on silicon, III−V heterostructures, thermal resistance.

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Light-emitting diodes (LEDs) based on gallium nitride (GaN), solid solutions AlGaN and InGaN, and other III−V semiconductor solid solutions are used widely at present in the fabrication of light sources [1]. The growth of III−V heterostructures is commonly performed on sapphire substrates. Since these substrates (especially those with a large diameter) have a number of drawbacks, efficient alternative materials have been actively searched for in recent years [1]. The use of hybrid silicon carbide on silicon (SiC/Si) substrates, which are fabricated using the method of coordinated substitution of atoms in a chemical reaction between the initial single-crystalline silicon and gaseous carbon monoxide (CO), is one of the viable options here [2,3]. Substrates of this type have the following significant advantages: lack of lattice mismatch dislocations in a SiC layer; fine matching of the lattice constants of GaN and SiC; and fine matching of the coefficients of thermal expansion of GaN and SiC. Specifically, the authors of [4,5] have succeeded in growing light-emitting heterostructures based on AlInGaN on hybrid SiC/Si substrates. A serious issue related to the removal of heat from a $p{-}n$ junction arose in the process of fabrication of LEDs based on these structures. The matter is that a pore layer forms in silicon beneath a SiC layer in the process of SiC growth from Si by coordinated substitution of atoms, since the volume of a single SiC cell of a cubic polytype is approximately two times smaller than the volume of a single Si cell [2,3]. The thicker a SiC layer is, the greater is the amount of SiC forming beneath the layer and the higher is the number of pores in a Si layer with a thickness of $1{-}5\,\mu$m below SiC. The pores themselves are partially filled with SiC, and the volume of this material is approximately equal to the volume of voids [2,3]. A question then arises: how does the porosity of Si affect the removal of heat from a $p{-}n$ junction in a light-emitting structure grown on SiC/Si? The aim of the present study is to examine this issue by measuring the thermal resistance of grown structures as a function of the SiC layer thickness.

The thermal parameters of grown SiC/Si structures were analyzed by comparing the values of thermal resistance. The method for examination of thermal resistance was based on the determination of transient temperature-dependent characteristics (forward $p{-}n$ junction voltage in response to an abrupt impact of a heating current pulse) with a Thermal Transient Tester T3Ster instrument [6], which performs measurements in accordance with the JESD 51-14 international standard [7]. The T3Ster software provides an opportunity to determine cumulative and differential structure functions [8] that illustrate the thermal impedance: thermal capacity and thermal resistance of elements of a thermal circuit (i.e., individual layers of the structure and interfaces between them). A similar method was used to examine the thermal parameters of polysiloxane-graphite composites [9].

Samples of hybrid SiC/Si substrates grown on boron-doped $50\,\Omega\cdot$cm Si(111) with a SiC thickness of 100, 200, and 400 nm and a clean boron-doped $50\,\Omega\cdot$cm Si(111) substrate (i.e., the sample with zero SiC thickness) were studied. Sections 1.15×1.15 mm in size were cut out of all samples with a diamond disk. The indicated dimensions correspond to those of an Epistar LED chip that was used as a heating indicator element. LED chips were secured to the studied SiC/Si samples with contactol, which has a thermal conductivity of 29 W/(m · K). The samples themselves were then secured with contactol to an aluminum heatsink. Thus, the thermal resistance between a $p{-}n$ junction of an Epistar LED and the aluminum heatsink with the studied sample mounted on it was measured in our experiments. A significant fraction of supplied electrical energy is converted into light in efficient LEDs. Therefore, the value obtained in electrical measurements (with T3Ster) of thermal resistance R_{th} of LEDs was corrected with account for output optical power P_{opt}. The structure of layers is presented in Fig. 1.

Figure 2 shows the cumulative structure functions for all four SiC/Si samples with different thicknesses. Near-horizontal sections correspond to a slight variation of thermal capacity and a considerable variation of thermal resistance; i.e., these are the regions of a sufficient thickness and low thermal conductivity. In contrast, near-vertical sections represent thin layers with a high thermal conductivity. Abrupt slope changes correspond to interfaces between different structure layers (heterostructure, substrate, metallization, etc.) [8].

It can be seen that the samples with a small SiC thickness (100 and 200 nm) and the clean Si substrate with zero SiC thickness are virtually indistinguishable and have exactly the same parameters of heat removal from the chip, whereas the heat removal efficiency of the sample with a SiC thickness of 400 nm is much lower. This is attributable to detachment of the 400-nm-thick SiC film from the Si substrate. The SiC layer has no thermal contact with the aluminum heatsink via silicon. The thermal circuit at SiC thicknesses below 200 nm is a series arrangement of the initial chip, contactol, the hybrid SiC/Si substrate, and the aluminum heatsink; at a SiC thickness of 400 nm, contactol and SiC/Si merge into a single element with a very high thermal resistance, and the process of removal of heat directly via the hybrid substrate thus ceases almost completely. The difference in structure of SiC/Si samples with a thickness of 200 and 400 nm is evident in microstructural cross-sectional images of these samples (Fig. 3).

It follows from Fig. 2 that the thermal resistance of SiC/Si at SiC thicknesses up to 200 nm is approximately equal to 2 K/W, which corresponds to a fine thermal conductivity; at a SiC thickness of 400 nm, the thermal resistance of the SiC/Si sample in combination with contactol is approximately equal to 250 K/W. Thus, it effectively turns into a thermal insulator due to the lack of a thermal contact between SiC and Si.

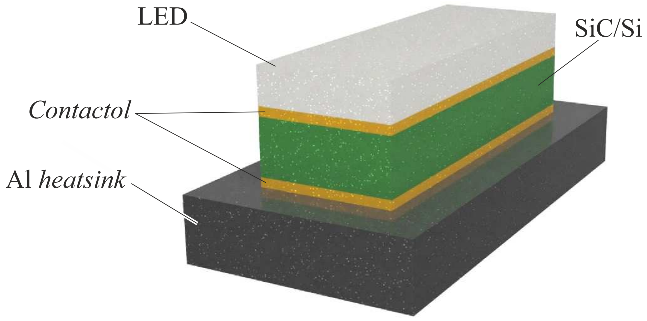

Figure 1. Schematic diagram of the studied SiC/Si samples on an aluminum heatsink.

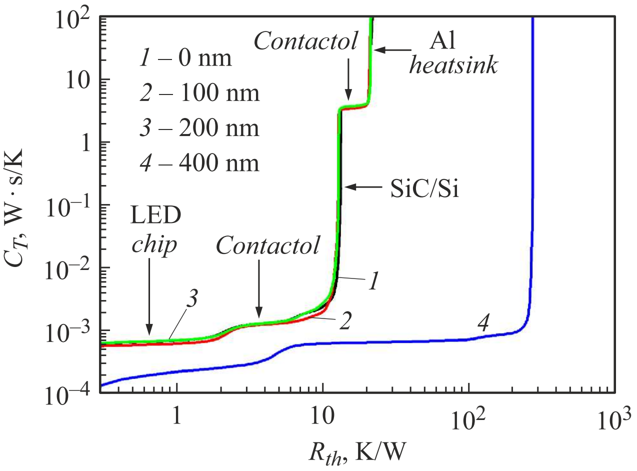

Figure 2. Cumulative structure functions for all four SiC/Si samples with different SiC layer thicknesses. The cumulative functions of samples with a SiC layer thickness of 0–200 nm are virtually indistinguishable, while the cumulative function of the sample with a 400-nm-thick SiC layer differs greatly from the others.

Thus, the obtained data suggest the following conclusion. Hybrid SiC/Si substrates with a SiC thickness up to 200 nm provide efficient removal of heat from a light-emitting $p{-}n$ junction. Specifically, SiC films with a thickness of 70 and 100 nm were used in [4,5]. Despite the presence of a porous layer, the thermal conductivity of a hybrid SiC/Si substrate is virtually equal to the thermal conductivity of pure silicon, since the thickness of SiC is small relative to the one of Si ($\sim 500\,\mu$m). A further increase in the SiC thickness (to values in excess of 200 nm) leads to the loss of thermal contact between SiC and Si; SiC/Si samples of this type can no longer serve as substrates for LED chips of the face-up design with light being output through transparent conducting contacts deposited on top of the *p*-region of a heterostructure. At the same time, such structures may be used efficiently in fabrication of flip-chip LED with an opaque reflective contact, which is mounted directly on a heatsink, deposited on top of the *p*-region of a heterostructure. As was demonstrated above, the removal of an opaque part of the substrate (needed for light output from a flip-chip LED chip) is maximally streamlined in the case of SiC/Si structures with a SiC layer thickness in excess of 200 nm. Light is then output through a transparent SiC layer of a hybrid substrate.

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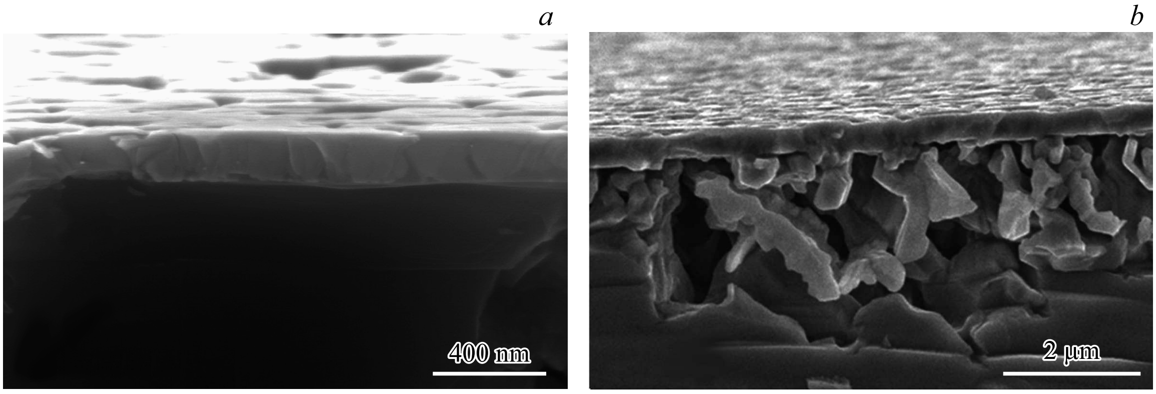

Figure 3. Microstructural cross-sectional images of SiC/Si samples with a thickness of 200 (*a*) and 400 nm (*b*).

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Conflict of interest

The authors declare that they have no conflict of interest.

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