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Thin-film LED based on AlInGaN layers grown on hybrid SiC/Si substrates

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We present the results of fabrication of flip-chip LEDs with removed substrate from AlInGaN heterostructures grown on SiC/Si substrates synthesized by vacancy-matching atom substitution. It is shown that SiC/Si substrates are optimal from the viewpoint of matching lattice parameters, thermal conductivity, and optical characteristics of the material at a significantly lower cost. Therewith, the procedure of cutting wafers into individual chips and removal of the opaque silicon part of the substrate becomes easier, and the transparent SiC part of the substrate remaining on the chip surface creates a relief that facilitates light output.

Keywords: thin-film LEDs, LEDs on silicon, LEDs on silicon carbide on silicon, AlInGaN heterostructures, SiC/Si.

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In connection with the widespread of LEDs based on AlInGaN heterostructures which are used as solid-state lighting sources and, most recently, also as ultraviolet (UV) radiation sources, researchers continue efforts to improve their design. As known, the range of substrates suitable for epitaxial growth of such a material as GaN is rather limited [1]. In view of matching the lattice parameters, thermal conductivity and optical parameters, the optimal substrates are those made from gallium nitride; however, large-size GaN substrates still remain unavailable. The next with respect to compatibility of the parameters are the silicon-carbide substrates. However, for the reasons of economy the vast majority of GaN-based LEDs rely on heterostructures grown on lower-cost leucosapphire substrates whose characteristics are inferior to those of SiC. When large diameters are needed (200−300 mm), a good alternative for growing GaN are silicon substrates; this is caused both by their cost and specific features of their treatment which have been comprehensively elaborated during many years of the silicon technology evolution. However, a significant mismatch of the crystal lattice parameters and thermal expansion coefficients of silicon and GaN prevented them from occupying an important niche at the market. To our opinion, an interesting possibility of growing GaN-based heterostructures consists in fabricating and employing substrates with a SiC layer grown on silicon substrate surfaces (SiC/Si). Such substrates are able to combine the main advantages of the silicon-carbide substrates with low prime cost and technological efficiency of the silicon substrates. Successful growth of GaN on such substrates was described in [2]; however, further investigations showed [3] that obtaining GaN of the necessary quality needs very thick SiC layers (thicker than $1\,\mu$m). The use of amorphous SiC [4] on the SiO_2/Si substrates in fabricating thin-film LEDs was also reported.

Paper [5] considers the procedure for fabricating face-up LEDs based on AlInGaN heterostructures grown on SiC/Si substrates synthesized by the coordinated atom-substitution method [6]. As shown in [5], the presence of growth pores on the SiC/Si interface improves the LED efficiency due to light diffusion on the interface and increases the radiation output efficiency. Nevertheless, to achieve maximal efficiency factors of chips on the SiC/Si substrates, it is necessary to remove the non-transparent part of the substrate.

Since the design of a heterostructure comprising the AlN nucleation layer, which is used for growing on the new-type SiC/Si substrates, does not ensure the required vertical conductivity of the heterostructure, the optimal solution seems to be to use the flip-chip LED design with subsequent removal of the opaque silicon part of the growth substrate. Remind that, in the case of the flip-chip assembling, the LED chip is mounted in the face-to-heatsink manner, namely, with epitaxial layers toward the heatsink, while light is released through the opposite heatsink surface. This design possesses a number of advantages over the above-mentioned face-up geometry and is used in developing high-power efficient LEDs operating at high current densities. Removal of flip-chip growth substrates and formation of so-called thin-film flip-chips (TFFC) promotes, even in the case of a transparent substrate, an additional increase in the LED quantum yield due to arising of a light-diffusing relief on the heterostructure boundary getting open after removing the substrate. Since contacts to the *n*- and *p*-region of the heterostructure are located on the same side of the chip (contrary to the so-called „vertical" LED chips

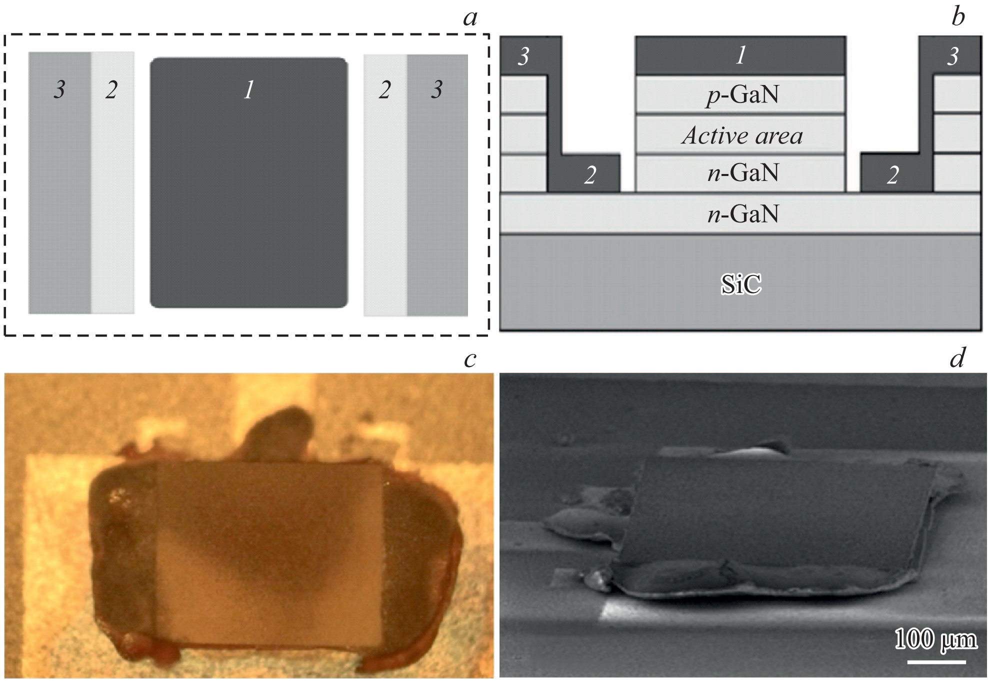

Figure 1. Schematic representation of the flip-chip LED design: optical-microscope image of the top view (*a*), cross-section (*b*), and appearance of the LED chip with removed silicon substrate (*c*), and electron-microscope image (*d*) from the side initially turned towards the silicon substrate (the light-diffusing crystals located on this side obscure the contacts located on the chip side). *1* — reflecting *p*-contact, *2* — *n*-contact, *3* — soldering area of the *n*-contact located at the same level with the *p*-contact.

that also imply removal of the growth substrate), TFFCs are demanded in fabricating UV LEDs whose heterostructures include a low-conductivity buffer layer [7,8].

The main drawback of the method of coordinated substitution of atoms [6] is that thickness of the SiC layer grown by this method is physically restricted. This method does not allow growing SiC layers thicker than 200 nm. In study [9], the method of coordinated substitution of atoms [6] was significantly improved; as a result, the method of vacancy-matching substitution of atoms was proposed and implemented. The method allows significant increase in the silicon carbide thickness in the process of atoms substitution. Notice that, being used in synthesizing SiC, this method provides not only an increase in the silicon carbide thickness, but also the silicon carbide detachment from the silicon substrate provided the SiC layer thickness exceeds 400 nm.

The detailed description of the growth technique and properties of InGaN/GaN LED structures on SiC/Si substrates is given in [10].

To practice all the post-growth operations, a simple configuration of contacts on the heterostructure surface was chosen, in which the rectangular *p*-region accommodating the contact was located on the chip axis (Fig. 1). On two opposite sides of the region, narrow rectangular mesa-structures intended for placing *n*-contacts were etched in the heterostructure. For the convenience of mounting the chip on the sub-chip board, the *n*-contact sites were leveled up to the *p*-region at the chip edges. The chip itself was a rectangle 0.7×0.56 mm in size; the $p-n$-junction area was $0.13\,\mathrm{mm}^2$.

The LED fabrication procedure consisted of a set of standard post-growth operations, including creating in the heterostructure a mesa-relief ensuring access to the heterostructure *n*-layer ($0.3\,\mu$m in our experiment) by ion etching in the Cl_2:BCl_3:Ar atmosphere, application of metal contacts to the *n*- and *p*-region of the structure, cutting the wafer into chips, mounting the chip on the sub-chip board, and removal of the silicon substrate. Notice that, in order to increase the LED quantum yield, it is reasonable to use in fabricating the metal contacts to both heterostructure regions the metals highly reflective at the LED self-radiation wavelength. Nevertheless, since in this study the task of practicing the main operations of TFFC fabrication on the SiC/Si substrates was set, materials chosen for the contacts to the *n*- and *p*-region of the heterostructure were the Ti/Au and Ni/Au metal combinations, respectively. We can notice a positive effect of using SiC/Si substrates instead of conventionally used sapphire ones; this effect stems from facilitation of the procedure for cutting the wafer into separate chips due to the possibility of using simpler tools because of lower hardness of silicon. In this work, diamond disks $20\,\mu$m thick were used.

For mounting the chips, sub-chip boards based on AlN ceramics were fabricated. The pattern of metallization regions formed on sub-chip boards and intended for arranging the chip and supplying electric current to it was determined by the shape of contacts of the chip itself. The substrate was removed by the liquid method. For this purpose, the chip mounted on the sub-chip board was submerged into an HF-based etchant. The chip was secured by using contactol which is more resistant to various chemical solutions used as etchants. Experiments performed with etchants of different types showed that the best results may be achieved by using a three-component mixture, namely, the hydrogen peroxide/hydrofluoric acid solution (H_2O_2:HF = 1:1) with a few droplets of Br. This etchant promotes efficient detachment of the SiC layer from the bulk silicon part of the substrate. Because of high porosity of the layer arising due to atom substitution, etching proceeds in a thin silicon layer on the SiC/Si interface, while the porous part remains attached to the continuous SiC layer. At the same time, it is not necessary to dissolve the total volume of silicon to remove the substrate, but only a thin interface layer of silicon gets slightly etched due to the presence of the porous layer. As a result, higher rates of the process are achieved, as well as its higher cost-efficiency and environmental safety, since the major part of the silicon substrate bulk remains intact and, hence, the process needs a lower amount of reagents. Moreover, the removed structure (Fig. 1) is free of cleavages, cracks or other damages typically arising during laser-aided removal of the sapphire substrates because of a sudden release of gaseous nitrogen resulting from the GaN decomposition. After removing silicon, the outer light-output surface of the chip appears to be covered by silicon-carbide crystallites with the typical size of hundreds of nanometers (Fig. 2). This is a transparent porous silicon-carbide layer cleaned by etching and having thickness of a few of micrometers. Since the typical dimensions of the layer components are comparable with the LED self-radiation wavelength, the layer diffuses light at the chip−environment interface, which helps the radiation release from the heterostructure. After removing the substrate, the chip does not need creation of additional relief for preventing total internal reflection in the heterostructure waveguide, which is economically advantageous since allows excluding high-cost and labor-consuming operation of creating light-output surfaces on the heterostructure outer boundary. Chips obtained in the experiments exhibited stable luminescence; however, to obtain maximal quantum yields of the devices it is necessary to optimize a number of technological operations involved in their fabrication. The electroluminescence spectrum of the obtained chips is presented in Fig. 3.

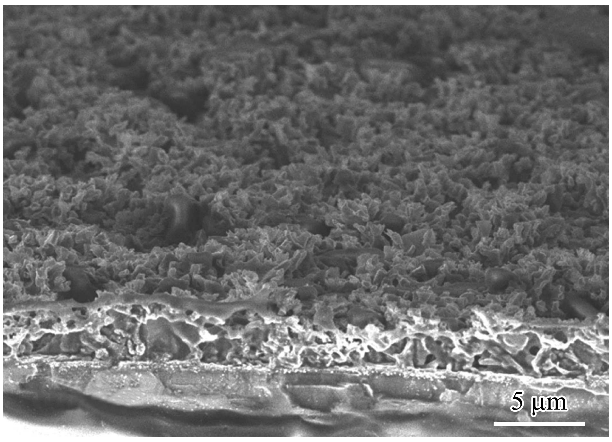

Figure 2. Raster Electron Microscope image of a LED chip with removed silicon substrate. Side view inclined at 15° to the chip surface.

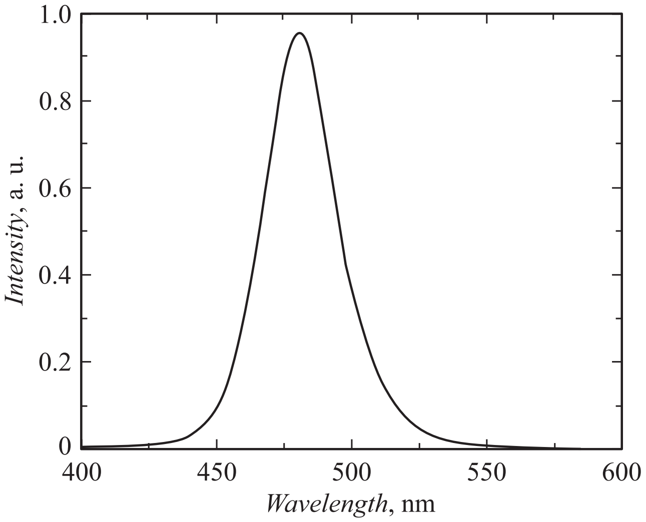

Figure 3. The LED chip electroluminescence spectrum.

Thus, we have developed a number of radically new approaches to fabricating TFFCs with removed substrate. The proposed technique has considerable advantages over the known methods for obtaining similar chips and may be used in developing the process of commercial production of such chips, including micrometer-size ones (micro-LEDs). The investigation results showed that the SiC/Si substrates are an innovative material for creating LED chips which is optimal with respect to matching the lattice parameters, thermal conductivity and optical characteristics of the material and low cost of the product.

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Conflict of interests

The authors declare that they have no conflict of interests.

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