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Blue Light Emitting Silicon-Carbide Diodes—Materials, Technology, Characteristics Appnote 31

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Introduction

Light-emitting diodes (LEDs) are widely used in the field of electronics as indicator lamps and seven-segment displays because of their excellent characteristics such as high mechanical stability, low operating voltage. compatibility with semiconductor drive circuits, low operating temperature and long service life. LEDs are now mass produced in colors: red, super-red, yellow and green. The semiconductor materials that are used are III-V compounds such as gallium arsenide phosphide ($GaAs_{1-X}P_X$) gallium phosphide (GaP) and recently, also gallium aluminum arsenide ($Ga_{1-X}A1_XAs$). An extension of the color of LEDs into the blue region of the spectrum has been wished by many users. The materials that are suitable for blue-light diodes are discussed here, followed by a survey of the technology and characteristics of blue-light diodes based on silicon carbide (SiC), the material that is preferred for this application by the Siemens company.

Semiconductor Materials for Blue-light Emitting Diodes

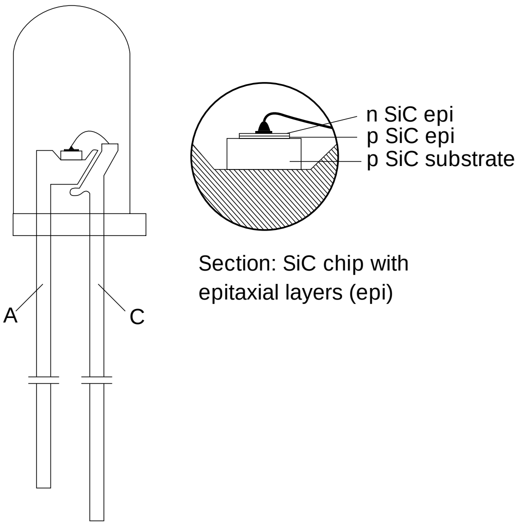
For emission in the blue region of the spectrum $GaAs_{1-X}P_X$ or GaP is out of the question because the band gap is too small, limiting the wavelength of the emitted radiation towards the lower end. But there are other semiconducting compounds such as gallium nitride (GaN), zinc sulfide (ZnS), zinc selenide (ZnSe) and silicon carbide (SiC). GaN was investigated quite intensively for the purpose of creating blue-light LEDs at the beginning of the 70s. With but one exception however, industrial research into this semiconductor material was then discontinued. The major drawback is the fact that GaN cannot be p-doped with sufficiently low resistance. Thus the light in this semiconductor is not produced by the radiative recombination of injected charge carriers at the pn junction as with the other III-V materials, but by highly accelerated electrons that are generated in the very high-resistance i layer of a metal-i-GaN-n-GaN layer by collision-ionization processes and thus lead to the emission of light. The efficiency of this mechanism, which results in higher operating voltages of the device, decreases with increasing current density (and thus luminous intensity of the diode). The situation is similar in the case of blue-light diodes using ZnS and ZnSe materials, in which likewise no low-resistance pn junction can be produced. The result of this is that with all the materials mentioned, despite the direct band-gap structure that is favorable for the generation of light and which leads to very efficient photoluminescence or cathodoluminescence for instance, the efficiency of the internal conversion of electrical energy into light is lower in comparison. SiC is the only material that allows reproducible p and n doping and possesses a suitable band gap for the emission of light in the blue region of the spectrum. The advantage of a device that can easily be controlled in all its physical characteristics more than makes up for the fact that SiC has an indirect band-gap structure, which is less favorable for generating light.

Groundwork on SiC blue-emitting LEDs has been performed in Great Britain, the USSR, Japan and in Germany at Hannover Technical University. Proceeding from the work done in Hannover, the development of SiC blue-emitting LEDs was pursued in the Siemens research laboratories and diodes were created with the highest efficiencies known to date. Siemens is one of the first semiconductor manufacturers to have successfully produced such diodes in the laboratory.

Technology and Design of SiC LEDs

An essential feature of SiC is its appearance in several modifications with different band gaps. For the production of blue-light LEDs the hexagonal modification 6H (αSiC) is the most favorable. As with all known LEDs, with SiC LEDs too the active light zone consists of epitaxial, monocrystalline material deposited on a p-type substrate crystal. The layer is grown from an Si melt saturated with carbon (liquid-phase epitaxy) at temperatures between 1600 and 1700°C, the p-type layer being doped with aluminum and the n-type layer additionally with nitrogen. The contacting and the diode structure are produced using the technologies already familiar with LEDs. The structure of an SiC lamp is shown in Figure 1.

Figure 1. Schematic of an SiC LED (dia. 5 mm)

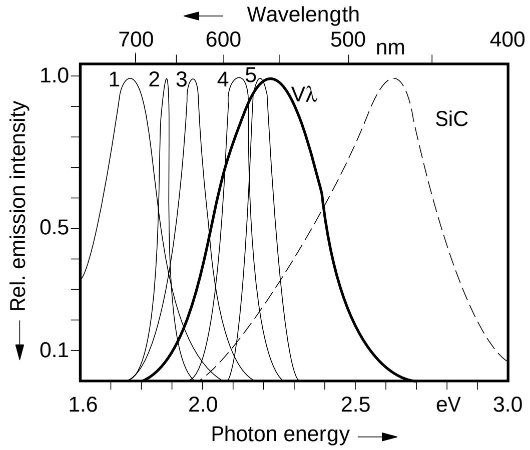


In addition to the high process temperatures, the major problem in SiC LED technology, compared to other semiconductor materials, is the lack of large-area substrate crystals—an absolute necessity where low manufacturing costs are concerned. Up to now it has been necessary to make do by preparing small crystal wafers of the appropriate modification from the kind of crystal clusters that appear as a by-product in the large scale industrial synthesis of SiC for producing grinding powder, but their diameter is no more than 10 to 14 mm. The big disadvantage of this is that the yield of suitable substrate crystals is only very small. At Siemens a substantial step towards a solution has now been taken. By means of a newly devised process, involving sublimation followed by condensation, monocrystals with a diameter of 15 mm and a length of 25 mm—that makes about 30 substrate wafers—were produced on a nucleus. This technology is, admittedly, considerably more elaborate than the technology of III-V semiconductors, so one cannot expect the price of blue-emitting diodes from SiC to fall to the level of more common LEDs; on the other hand though, an appreciable step towards mass production has thus been taken.

Characteristics of SiC LEDs

The emission spectrum of SiC LEDs and the dependence of the light current on diode current are illustrated in Figures 2 and 3 in comparison with other LEDs. Figure 4 shows the color locations of different LEDs on a standard color diagram. Whereas the red, yellow and green emitting diodes lie practically on the spectrum locus, the blue emitting SiC diodes exhibit two peculiarities. Their color location is not on the spectrum locus, and the dominant wavelength experienced by the observer shifts slightly with increasing diode current towards shorter wavelengths. Associated with this is a decrease in the rise and decay time of the luminescence from typically 0.9 µs (90-10%) at 5 mA to typically 0.5 µs at 50 mA. For a diode current of 20 mA the diodes have a luminous intensity of typically 4 mcd, the luminous efficiency being approximately 10^{-2} lm/V. A typical current/voltage characteristic is shown in Figure 5.

Figure 2. Photopic luminosity (normal vision) V, and emission spectra of different light-emitting diodes

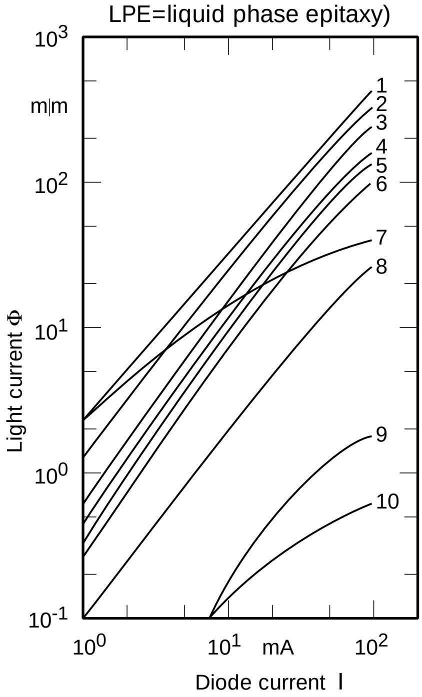


1 GaP:Zn,O
2 $GaAs_{0.6}P_{0.4}$ and $Ga_{0.65}Al_{0.35}As$
3 $GaAs_{0.35}P_{0.65}$:N
4 $GaAs_{0.15}P_{0.85}$:N
5 GaP:N

Based on $GaAs_{1-X}P_X$, GaP, Ga_{1-X}, Al_XAs and SiC in the visible spectral range

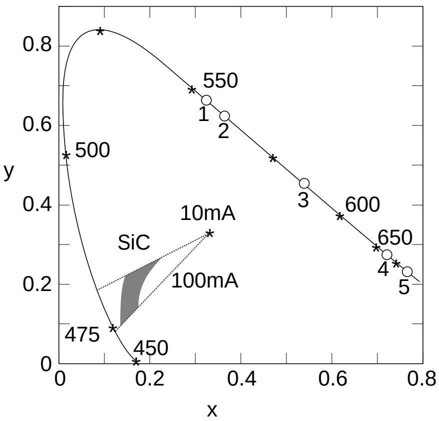
Figure 3. Light current/diode current characteristics Φ (I) of different LEDs

(VPE=vapor phase epitaxy, LPE=liquid phase epitaxy)



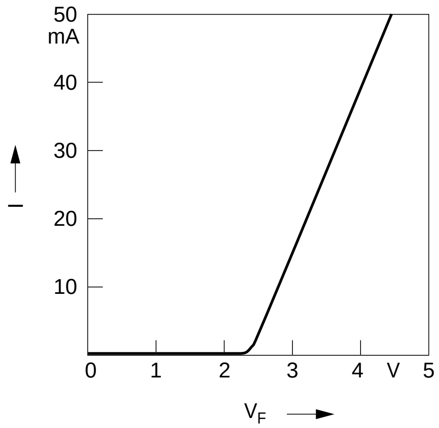
1 $Ga_{0.65}Al_{0.35}As$-LPE
2 GaP:N-LPE
3 $GaAs_{0.35}P_{0.65}$:N-VPE
4 GaP:X-LPE
5 $GaAs_{0.15}P_{0.85}$:N-VPE
6 GaP:N-VPE
7 GaP:NZn,O-LPE
8 $GaAs_{0.6}P_{0.4}$-VPE
9 SiC:Al,N-LPE
10 GaN-MiS-VPE

Figure 4. Color location of SiC LEDs (dotted) compared to other LEDs



1	GaP:X	4	GaP:Zn,O and $GaAs_{0.35}P_{0.65}$:N
2	GaP:N		
3	$GaAs_{0.15}P_{0.85}$:N	5	$GaAs_{0.6}P_{0.4}$ and $Ga_{0.65}Al_{0.35}As$

Figure 5. Current/voltage characteristic I (V_F) of a typical SiC LED



Applications and Prospects

The possible applications for SiC LEDs are all those in which small light emitters are required that are capable of emitting in the blue spectral range and are suitable for fast modulation (up to 500 kHz), in the scientific and technical field as a calibration light source for photomultipliers for example, in TV-camera engineering and photography, and as a radiation source in spectroscopy, biophysics and medicine.

It will no doubt be possible to make this technology cheaper through continuing development of the individual process steps that are involved. It should be emphasized once more, however, that the fundamental problems of SiC technology are such that the prices of conventional LEDs are not likely to be approached. This does not only apply to SiC, incidentally, but also to the other materials being considered for blue-light emitting diodes.