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Strongly directional emission from AlGaAs/GaAs light-emitting diodes

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We show for the first time that strongly directional emission of defined polarization can be achieved from conventional AlGaAs/GaAs double-heterostructure surface-emitting light-emitting diodes (LEDs) via coupling to surface plasmons. By microstructuring the surface, we have fabricated LEDs with a beam divergence of less than 4° and an increased quantum efficiency. It is demonstrated that the surface plasmon excitation and emission mechanism have the potential to improve the performance of LEDs.

Infrared light-emitting diodes (LEDs) and laser diodes are the most important sources for optical fiber communication. The advantages of LEDs compared to laser diodes include higher temperature operation, smaller temperature dependence of the emitted power, simpler device construction, and simpler drive circuits. Among the disadvantages are low external quantum efficiency (QE), lower modulation frequency, and wide spectral linewidth. Nondirectional emission is a detrimental property of both laser diodes and LEDs.[1]

Several efficient LED configurations were designed to improve the performance of LEDs. It was shown that the external quantum efficiency of LEDs can be increased by up to an order of magnitude by lensing or appropriately sculpturing semiconductor material above the emission region.[2-5] Low beam divergence and increased coupling to optical fibers is achieved by lenses cemented to the LED surface[6] or by lenses that are integral with the LED structure.[7]

In this letter we show for the first time that excitation and light emission of surface plasmons (SPs) represent another efficient method to improve LED performance with regard to specific technical applications. By the use of an appropriate surface grating we have achieved strongly directional emission and a drastically increased external QE from conventional AlGaAs/GaAs double-heterostructure LEDs.

In the past, light emission of SP has been investigated in several devices.[8-15] Sharp and narrow-band emission peaks due to the radiative decay of SP were obtained from periodically structured metal-oxide-metal junctions, when appropriately biased.[16-19] Theis *et al.*[20] achieved light emission of SP from charge injection structures. Recently, we have reported SP enhanced light emission from forward and reverse biased Ag/*n*-GaAs Schottky diodes.[21] If the surface of the diodes is periodically structured and coated with a thin metal film, photons generated in the GaAs substrate are first coupled to surface plasmon excitations, which then decay at the Ag surface into photons.

This coupling mechanism, based upon the excitation and light emission of SP, has the potential to improve the performance of LEDs. It overcomes basic external quantum efficiency losses, provides strongly directional emission of defined polarization, and reduces the linewidth of emitted light.

The light emission of periodically structured AlGaAs/GaAs double-heterostructure diodes LED_1 and LED_2 and of a flat diode LED_3 is investigated. The gratings are fabricated by electron beam lithography and reactive ion etching. The grating periods of LED_1 and LED_2 are $\Lambda_1 = 830$ nm and $\Lambda_2 = 1024$ nm with grating amplitudes of $H_1 = 40$ nm and $H_2 = 60$ nm. An Ag film of 25 nm thickness is evaporated on the front surface to form both an ohmic contact and to provide excitation of SP. The geometry of the samples is shown in the inset of Fig. 1.

The coupling mechanism is explained for the case of an emission wavelength of $\lambda = 867$ nm in Fig. 1: the light lines in air [curve (1)] and in GaAs [curve (2)] and the dispersion relation of SP at the Ag-air interface[22] [curve (3)] are plotted as a function of the wave vector. The additional curves represent the light lines of photons, which couple to SP due to the existence of the periodic surface structure.

Two basic loss mechanisms limit the external QE of LEDs: Photons generated in the active region have to be coupled out into air, but a portion of the light is reflected at the semiconductor/air interface (Fresnel loss); photons impinging on the interface with an emission angle Δ larger than the critical angle of internal total reflection ($\Delta_c \approx 16°$) cannot propagate into air (critical angle loss). However, if the surface of the LEDs is periodically structured and coated by a thin metal film, both loss mechanisms can be considerably reduced due to the excitation and emission of SP. Photons with p polarization (i.e., the magnetic field vector is parallel to the grating grooves) generated in the active layer can interact with SP according to the grating coupling condition:

$$k_{SP} = (\omega/c) n_{GaAs} \sin \Delta_l + l k_g, \tag{1}$$

with k_{SP} the wave vector of SP, n_{GaAs} the refractive index of GaAs, $k = 2\pi/\Lambda$ the grating vector and l an integer. In the case of LED_1, photons with $\Delta_{+1} = 0.4°$ directly pass through the metal film or interact via one grating vector [$l = +1$, process (A)] with SP. Photons with emission angle Δ_0 slightly larger than Δ_c couple directly to SP [light

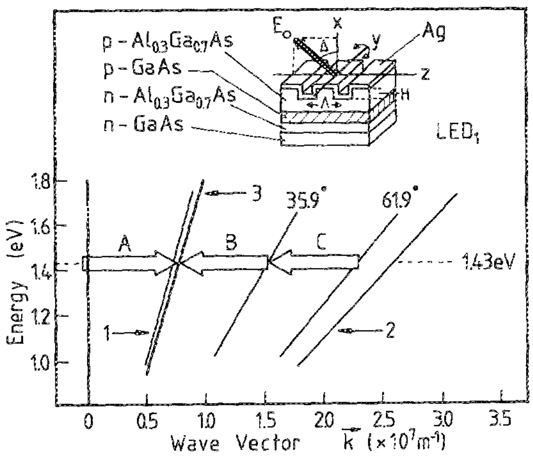

FIG. 1. Curves (1) and (2) represent the light lines in air and GaAs, respectively. Curve (3) shows the dispersion relation of SP at the Ag-air interface. The other curves represent possible light lines of photons generated in the active layer (p-GaAs), which couple directly to SP according to Eq. (1), indicated as processes A, B, and C.

line for $\Delta_0 = 16.8°$ intersects the SP dispersion curve (3)]. Photons with $\Delta_{-1} = 35.9°$ (32° for LED_2) and $\Delta_{-2} = 61.9°$ (50.2° for LED_2) couple to SP for $l = -1$ [process (B)] and $l = -2$ [process (C)].

Subsequently the excited SP radiates into air according to the grating coupling condition

$$k_{ph} = (\omega/c)\sin \Delta_l = k_{SP} + lk_g\,, \qquad (2)$$

with k_{ph} the wave vector of photons and Δ_l the angle of emission. For LED_1 coupling occurs only for $l = -1$ [inverse to process (A)] and results in an emission angle $\Delta_{-1} = 1.3°$. For LED_2 coupling is possible for $l = -1$ and $l = -2$ and emission occurs into two angles $\Delta_{-1} = 11°$ and $\Delta_{-2} = 40.5°$.

All coupling processes besides process (A) involve photons with emission angles Δ larger than Δ_c. Therefore the SP excitation and emission mechanism drastically reduces losses due to internal total reflection. In addition a reduction of the Fresnel loss at SP resonance is achieved due to the special property of the surface plasmon excitation. The result is an overall increase of the external QE; At an injection current of 20 mA LED_1 has an external QE of 1.51%, LED_2 of 1.40%, while LED_3 has a QE of 1%. The higher QE of LED_1 compared to LED_2 points out the essential importance of coupling photons with large emission angles to SP. As the refractive index of the active region is larger than the index of its surrounding AlGaAs layers, light is mainly guided in a direction parallel to the layer interfaces. Therefore the photons have rather large emission angles and are confined within the active layer. The emission angles of the photons which couple to SP are larger for LED_1 (35.9° and 61.9°) than for LED_2 (32° and 50.2°), so more photons interact with SP in case of LED_1.

The resulting radiation patterns are shown in Figs. 2 and 3. All emission measurements were performed at room temperature. The samples were mounted on a rotation stage with the grating grooves parallel to the axis of rotation (y axis). As shown in the inset of Fig. 1, the emitted

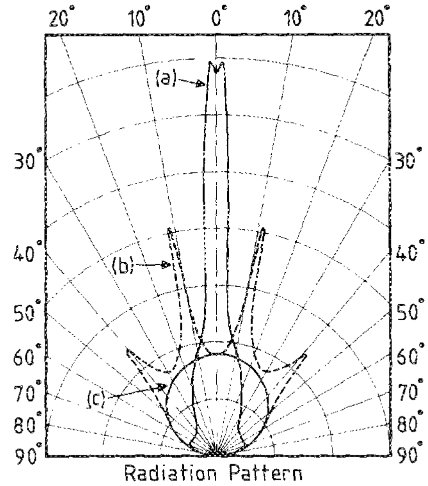

FIG. 2. Spatial distribution of the spectral light emitted from structured and flat LEDs. Curves (a) and (b) show the p-polarized radiation pattern of LED_1 and LED_2. Curve (c) represents the s-polarized radiation pattern of LED_1, LED_2, and LED_3. Light emitted from the flat LED_3 is completely unpolarized so curve (c) also represents the p-polarized radiation pattern of LED_3.

light (E_0) was detected in the (x-z) plane, while the angle Δ was varied. The spatial distribution of the spectral emitted light was detected with a solar cell. To determine the radiation pattern at maximum emitted wavelength, the emitted light was sent through a monochromator and detected with a photomultiplier.

Curves (a) and (b) of Fig. 2 show the spatial distribution of p-polarized light emitted from LED_1 and LED_2 at an injection current of 20 mA. LED_1 shows strongly directional emission around 0° with a beam divergence (i.e., spatial width at half emitted intensity) of 4°. The small dip at 0° indicates that the emission peak is composed of two immediately adjacent peaks. A slightly different grating period would result in emission perfectly focused in 0°. LED_2 shows emission peaks at 11° and 40.5° [curve

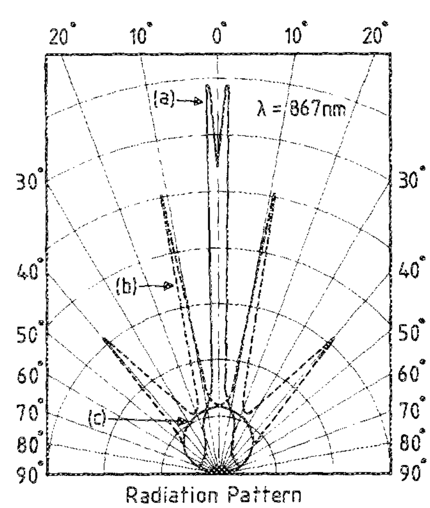

FIG. 3. p-polarized radiation pattern of LED_1 [curve (a)] and LED_2 [curve (b)] at the maximum emitted wavelength of $\lambda = 867$ nm. Curve (c) represents the s-polarized radiation pattern of both LED_1 and LED_2 and the radiation pattern of LED_3.

(b)]. The intensity of s-polarized emitted light is the same for LED_1, LED_2, and LED_3, as it is not influenced by excitation and emission of SP [curve (c)]. The total light emitted from the flat LED_3 consists of s- and p-polarized radiation of the same intensity.

The radiation patterns of LED_1 and LED_2 at the maximum emitted wavelength of $\lambda = 867$ nm are shown in Fig. 3 as curves (a) and (b). LED_1 shows directional emission with a beam divergence of 4°. Curve (c) represents the s-polarized far-field pattern of LED_1 and LED_2 and the unpolarized far-field pattern of LED_3.

The radiation patterns are due to the angular emission properties of the SP; excitation and subsequent radiative decay of SP result in strongly directional emission, as was also shown for sinusoidally structured Ag films.[23] Because of different experimental configurations, however, it is very difficult to compare our results with experimental results on sinusoidal gratings.

Excitation and emission of SP decrease the spectral linewidth of the emitted light, the full width at half maximum decreases at maximum emitted intensity from 36 nm for the flat LED_0 to 27.5 nm for LED_1 and LED_2.

Based upon the presented results, the performance of conventional LEDs can be designed for certain technical applications such as coupling of light into optical fibers or coupling into waveguides, the grating period determines the angle of directional emission. Therefore the emission angle, Δ, can be arbitrarily changed by a proper choice of the grating period. A reduction of the distance between the periodically structured surface and the active layer enhances the coupling efficiency between photons and SP and makes it possible to increase the external QE. Note that for the present grating configuration, the emission is enhanced only for p-polarized light. The use of a crossed grating provides coupling out of s-polarized light, which will additionally increase the external QE. Appropriate combinations of the SP coupling mechanism and current techniques, as for example lenses cemented to the LED surface, can result in further improvements.

Obviously this principle can be applied to the realization of vertical emitting laser diodes. In the laser situation photons travel parallel to the surface ($\Delta = 90°$). Two requirements have to be met to achieve laser operation via SP. First the distance between the Ag surface and the active layer has to be small to provide sufficient overlap between the electric fields of photons and SP. Second the grating period has to be adjusted according to Eq. (2). This technique has a high potential to achieve emission from laser diodes normal to the surface.

In summary, we have shown for the first time that strongly directional emission of defined polarization can be achieved from AlGaAs/GaAs surface-emitting LEDs by SP excited on a periodically structured surface. Using appropriate grating parameters, we have fabricated LEDs with a beam divergence of less than 4° and an increased external QE. The presented results prove that the SP coupling mechanism has the potential to improve the performance of LEDs. Applications of this principle to vertical emitting laser diodes are in progress.

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