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Semiconductor distributed Bragg reflectors for vertical-cavity surface-emitting diode lasers

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In the present work, semiconductor distributed Bragg reflectors (DBRs) used in vertical-cavity surface-emitting diode lasers are described in detail. In the case of AlAs/AlGaAs heterostructures, even less than 20 periods of quarter-wavelength DBRs are enough to produce reflectivity as high as over 99.5%. Series problems connected with potential barriers at heterostructure interfaces may be partly overcome with the aid of graded layers, stair-case layers or superlattice interfaces. But they still need some essential improvement.

1. Introduction

Optical cavities of vertical-cavity surface-emitting (VCSE) diode lasers are situated orthogonally to those of conventional edge-emitting (EE) devices [1], whose resonator mirrors are usually formed by simple cleaving. In comparison with EE lasers, VCSE lasers are characterized by much shorter gain lengths; therefore, to reduce their end (edge) losses, much higher (close to unity) mirror reflectivities must be used.

At the very beginning, VCSE lasers were usually equipped with dielectric mirrors (for review see, e.g., [2]), whose application, however, was followed by two essential disadvantages:

— necessity of performing an additional technological step to produce dielectric films using evaporation technique,

— problems with achieving mirror reflectivities high enough for VCSE lasers.

Therefore, in practically, all modern constructions of VCSE lasers, semiconductor distributed Bragg reflectors (DBRs) are used, sometimes supported by metallic mirrors.

In this paper, semiconductor distributed Bragg reflectors in application to VCSE lasers are presented in detail. Those reflectors consist of semiconductor layers (e.g., AlGaAs and AlAs) of the alternating high and low refractive indices. In the following, we focus first on the design of DBR structures, introducing analytical simple formulae necessary to determine their reflectivity coefficients. The formulae are

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given not only for sole semiconductor DBRs, but also for compound mirrors where an additional metal layer is used to enhance the reflectivity. Then, we consider the use of DBR mirrors with graded interfaces, intermediate stair-case layers or superlattice interfaces to reduce an electrical resistance of DBR structures so that electrical power dissipation in the mirrors is minimized. Finally, the AlAs/AlGaAs and InP/InGaAsP DBR structures are compared.

2. Reflectivity of DBR structures

2.1. Abrupt interfaces

Let us consider a multilayer quarter-wavelength semiconductor stack with abrupt interfaces (Fig. 1**a**). Then, its effective field reflectivity is given by [3], [4]

$$r = \tanh\left[\sum_{i=1}^{N} \tanh^{-1}(r_i)\right] \tag{1}$$

where N is the number of interfaces, and r_i is the field reflectivity caused by dielectric discontinuity at each interface

$$r_i = \left|\frac{n_{i+1}-n_i}{n_{i+1}+n_i}\right| \tag{2}$$

with n_i standing for the index of refraction in the layer before the i-th interface.

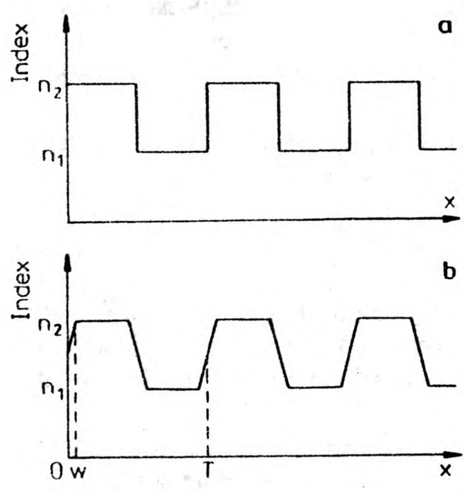

Fig. 1. Index profile typical of a quarter-wavelength stack [6]: with abrupt interfaces (**a**) and with graded intermediate layers (**b**). T — thickness repetition period, w — 1/2 of the graded layer thickness

2.2. Graded interfaces

In the case of the structure with graded intermediate layers between the constituent two layers of DBR mirrors (Fig. 1**b**), i.e., with graded interfaces (the necessity of their introducing will be backed up later in Sect. 3.2) Eq. (1) remains still valid, but with new expression for r_i, which must be derived. Let us first consider the coupling constant K using the coupled mode theory [5]. For abrupt interfaces, it may be expressed by

$$K_a = \frac{2|n_{i+1} - n_i|}{\lambda_0} \tag{3}$$

where λ_0 is the free-space wavelength. Analogous relation for the structure with graded layers (Fig. 1b) may be written in the following form [6]:

$$K_{gr} = K_a[\sin(2\pi w/T)/(2\pi w/T)] \tag{4}$$

where T is the repetition period of the stack, and w is half of the graded layer thickness. Then, the field reflectivity r_i becomes [6]

$$r_i = \tanh[K_{gr}\lambda_0/2(n_i + n_{i+1})]. \tag{5}$$

2.3. Compound mirrors

Sometimes, to reduce the number of layers in the rear semiconductor DBR mirror, this mirror is supported by adding a metal layer [7] – [12]. It is also possible in the case of a front mirror, where sometimes a semitransparent metal layer is used [13] – [17]. In this case, however, a penetration of the radiation wave into the metal must be taken into account. Then, a thickness of the semiconductor layer just

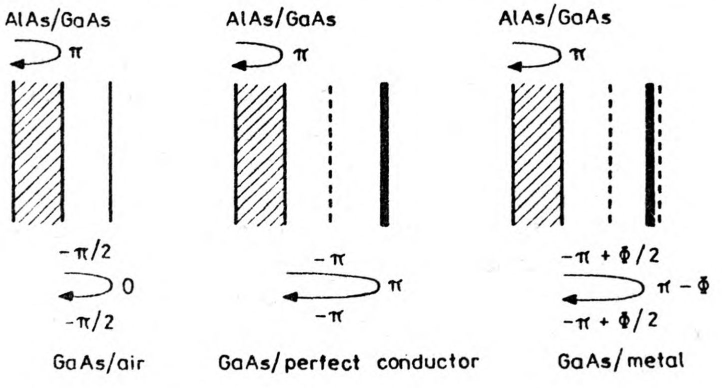

Fig. 2. Phase matching condition for three different mirror terminations. The phase shift for propagation through a layer and reflection from an interface are shown in radians. For proper phase matching, the phase of the final reflection should be equal to phase of the previous reflection (at the AlAs/GaAs interface), (modulo 2π). For an air termination, a quarter wavelength of GaAs should be used. For a perfect conductor with infinite conductivity, a half wavelength should be used. For a realistic metal, the thickness of the GaAs should be reduced from a half wavelength to compensate for the finite penetration depth into the metal [6]

before the metal layer must be slightly reduced to insure correct phasing. This case is illustrated schematically in Fig. 2, where also two other mirror terminations are considered. Then, the power reflectivity coefficient is given by [6], [18]

$$R = [(n_a - n_m)^2 + k_m^2]/[(n_a + n_m)^2 + k_m^2], \tag{6}$$

and the Φ_m phase shift upon the reflection may be written as [6], [18]

$$\Phi_m = \pi - \Phi \tag{7}$$

with

$$\Phi = \tan^{-1}[2n_a k_m/(n_m^2 - n_a^2 + k_m^2)]. \tag{8}$$

In the above formulae, n_a is the index of refraction of the material adjacent to the metal layer, and n_m and k_m are the index of refraction and the extinction coefficient of the metal, respectively.

2.4. Numerical examples

Let us apply the above formulae for VCSE structures. In their designing, it is essential to determine a minimal number of DBR mirror layers to achieve a needed reflectivity. For example, the reflectivity as high as 0.9950 [6] is obtained for an 18.5 period mirror composed of alternating AlAs – GaAs quarter-wave layers with abrupt interfaces. This value is slightly reduced to 0.9941 [6], when the interfaces between the GaAs and the AlAs layers are linearly graded over 18 nm. But the addition of only one extra mirror period raises this value up to 0.9958 [6].

As it was stated earlier, the necessary number of semiconductor layers in a DBR mirror may be considerably reduced without any reduction in the reflectivity coefficient of the resonator mirror, when an additional metal layer is placed on the top of the DBR stack. For an Au layer and $\lambda_0 = 980$ nm: $n_m = 0.117$ and $k_m = 5.973$ [19]. So, we can calculate the phase shift Φ from Eq. (8): $\Phi = \pi/3$, and the field reflectivity r_m from Eq. (6): $r_m = 0.974$ [6]. Those values must be used in Eq. (1) and Eq. (7) to determine the number of semiconductor layers in the DBR reflector necessary to achieve a given reflectivity of the composite mirror and the thickness of the semiconductor layer adjacent to the metal layer. It appears that application of an additional Au mirror enables us to reduce the number of layer periods with graded interfaces to only 7.5, preserving even higher reflectivity than previously: $R = 0.9966$. But to assure the phase matching, a thickness of the last semiconductor layer just before the metal layer must be reduced from 0.5λ to 0.417λ, where λ is the wavelength of radiation inside this layer.

3. Series electrical resistance of DBR structures

3.1. Potential barriers

The index difference between the two constituent layers of semiconductor distributed Bragg reflectors is responsible not only for high optical reflectivity, but also for energy bandgap difference which results in potential barriers (see Fig. 3b). These barriers impede the carrier flowing in the DBR structure. This results in a large series electrical resistance (even several tens of kiloohms), which causes an intense heat generation and thus deterioration of laser performance.

Potential spikes are formed in the heterointerfaces due to the space charge. Barrier heights ΔE_v are nearly as high as the valence-band offset which, e.g., for the p-type GaAs/$Al_{0.7}Ga_{0.3}As$ heterostructure is equal to 0.25 – 0.30 eV and is much higher than the 26 meV thermal energy at room temperature. Electrical conduction in this structure comprises thermionic emission current I_{th} over the barrier and quantum-mechanical tunnelling current I_{tu} through the barrier [20]:

$$I_{th} = I_1 \exp(-\Delta E_v / k_B T), \tag{9}$$

$$I_{tu} = I_2 \exp(-\beta \Delta E_v) \tag{10}$$

where I_1 and I_2 are the proportional constants, k_B is the Boltzmann constant, and β is given by

$$\beta = (1/\hbar e)(4m^* \varepsilon / N_A)^{1/2}, \tag{11}$$

with $\hbar$ – Planck constant, e – electron charge, m^* – hole effective mass, ε – electric permittivity, and N_A – acceptor concentration. For n-type mirrors, the above effects are much less severe and their resistance is believed to be caused mostly by poor conductivity of AlAs [10].

3.2. Non-abrupt interfaces

A possible solution to this problem, i.e., application of graded intermediate layers between both constituent layers of the DBR structure, was proposed by BAETS et al. [21]. The method is explained in Fig. 3, which shows schematically energy-band diagram of undoped and p-type DBR doped structures for abrupt and graded

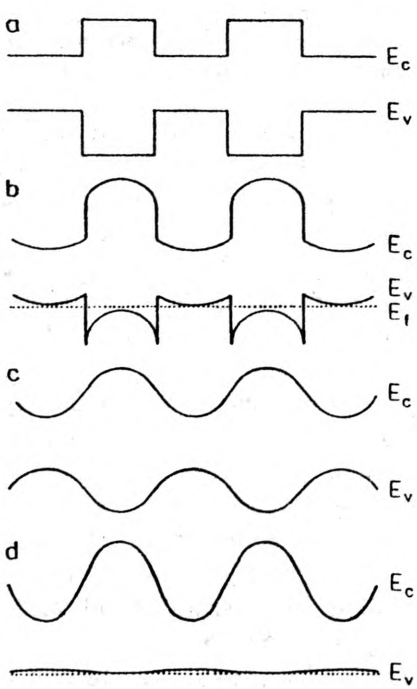

Fig. 3. Section of energy-band diagram of QW–DBR mirror, which consists of quarter-wavelength high-index (low band gap) and low-index (high band gap) compound semiconductor stacks. The following cases are considered:undoped quarter-wavelength DBR structure (a), p-type quarter-wavelength DBR structure (b), proposed undoped modified DBR structure with gradual composition variation (c), proposed p-type modified DBR structure with gradual composition variation (d). The energy-band diagrams for p-doped heterostructures were reshaped because of the space charge [20]

interfaces. In the modified structure, i.e., with graded interfaces, the valence-band energy diagram (Fig. 3d) is almost flat, which seems to eliminate the series resistance problem. As it was explained earlier in Sect. 2.4, the introduction of graded interfaces in DBR structures affected only slightly their reflectivities which may be easily compensated by adding one mirror period.

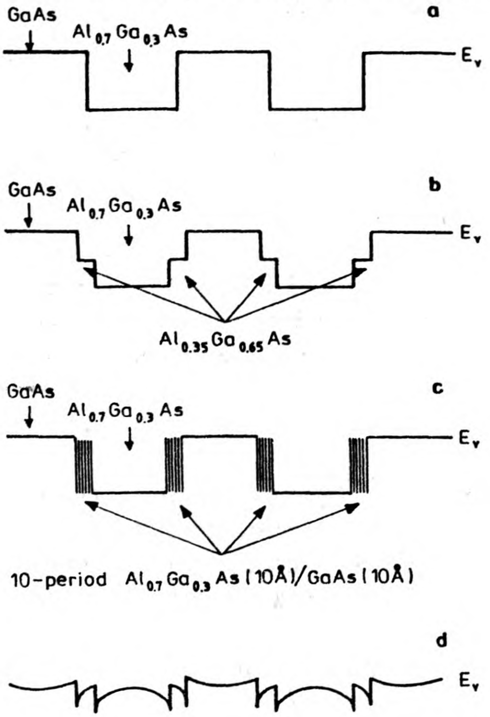

Fig. 4. Section of the valence-band diagram for DBR semiconductor mirrors with: abrupt interfaces (a), stair-case intermediate layers (b), super-lattice interfaces (c), without considering the band-bending effect due to space charge. The valence-band diagram for the p-doped stair-case DBR structure, where the above effect was taken into consideration, is plotted in (d), [20]

TAI et al. [20] proposed alternative solutions to the above problems, namely the DBR structures with stair-case intermediate layers (Fig. 4b) and with super-lattice interfaces (Fig. 4c), which are simpler from technological point of view. All the above modifications to the DBR mirrors, i.e., graded interfaces [8], [22], [23], super-lattice interfaces [7], [9], [24]–[28] and stair-case interfaces [16], [17], [29]–[33] were successfully adopted. But heating problems connected with still high series electrical resistance (several tens to few hundreds ohms) still remain unsolved, although they are not as severe as previously.

Barrier widths in the DBR structures may be reduced by increasing their doping levels [34]. Then the tunnelling component (10) of electrical conduction through the barrier will be enhanced decreasing the series resistance of the DBR structure. A penalty paid for it is an increase in free carrier absorption losses. An essential improvement of the DBR structure was proposed by WALKER et al. [22] and HASNAIN et al. [35], who applied higher doping to all mirror layers, except for the last few pairs near the active region, where the radiation intensity is significantly higher. Using this method, WALKER et al. [22] designed a 45×45 μm VCSE laser with graded interfaces whose series resistance at threshold was as low as 18 ohms.

The manufacturing of modified DBR structures is very complicated. Therefore, an intense effort is undertaken to invent such VCSE constructions, where the current paths will omit high-resistive DBR structure. This is realized, e.g., in a mushroom VCSE laser [36], where selective zinc diffusion forms lateral conducting paths with lower resistance while leaving intact the DBR structure above the active region. Similar solutions, i.e., VCSE lasers with air bridges, are proposed in [37]–[39].

4. Comparison between the AlAs/AlGaAs and the InP/InGaAsP DBR structures

Let us now compare the AlAs/AlGaAs and the InP/InGaAsP distributed Bragg reflectors. In the first case, a refractive index difference between component layers of DBR structures is as high as ca. 0.5, therefore, even less than 20 periods are necessary to produce 99.5% reflectivity, as was shown in Sect. 2.4. Then, the AlAs/AlGaAs DBR structures (without a substrate) are as thin as 5–6 μm only.

A much worse situation is in the case of the InP/InGaAsP distributed Bragg reflectors. For this heterostructure, the refractive index difference is much lower, only 0.2–0.3, therefore, about twice as many periods of DBR mirrors are needed [40], [41] as for the AlAs/AlGaAs structure. Each layer must also be much thicker, because of longer wavelengths of emitted radiation (1.3–1.55 μm vs. 0.85 μm). As a result, the total InP/InGaAsP VCSE structure would be thicker than 20 μm. Therefore, practical VCSR lasers within 1.3–1.55 μm range will very probably have dielectric mirrors.

In the case of small-diameter VCSE lasers, surface recombination becomes a very serious problem [42]–[45]. For 1.3–1.55 μm InP/InGaAsP devices, however, the recombination velocity is about 100 times less [46], which causes the problem to be much less severe.

5. Conclusions

Semiconductor distributed Bragg reflectors in application to VCSE diode lasers have been described in the present paper. While their present optical properties seem to be suitable enough to manufacture modern and efficient VCSE diode lasers, electrical properties, strictly speaking high values of series electrical resistances, still need some essential improvement.

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