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New type of heterogeneous nanophotonic silicon-on-insulator optical waveguides

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***Abstract*. A new type of optical waveguides in silicon-on-insulator nanostructures is proposed and studied. Their optical properties are simulated by the beam propagation method and discussed. A new design in the form of heterogeneous waveguide structures is based on the production of additionally heavily doped p^+-regions on the sides of a multimode stripe waveguide (the silicon core cross section is ~ 200 nm $\times$ 16 μm). Such doping provides the 'single-mode' behaviour of the heterogeneous waveguide due to the decrease in the optical losses for the fundamental mode and increase in losses for higher-order modes. Single-mode heterogeneous waveguides can be used as base waveguides in photonic and integrated optical elements.**

Keywords: *integrated optics, optical waveguide, optical losses, silicon-on-insulator.*

Optical waveguides based on thin silicon-on-insulator (SOI) nanostructures are widely used in various photonic elements [1] whose production technology can be compatible with the standard complementary metal – oxide – semiconductor (CMOS) technology. Because of a high contrast of the refractive indices of the silicon core ($n = 3.478$) and surrounding oxide ($n = 1.447$), single-mode SOI waveguides have the core of submicron size and comparatively high losses [1].

The manufacturing technology of thin SOI waveguides is compatible with that of photonic crystals, which can be used for manufacturing two-dimensional diffraction gratings [2] for coupling light from optical fibres along the normal to nanowaveguides. However, due to a high contrast of the refractive index, it is impossible to fulfil simultaneously incompatible requirements imposed on the optimal geometrical dimensions of the silicon core of the waveguide. To reduce parasitic signals, the waveguide should be single-mode, i.e. it should have the submicron size. In the direction perpendicular to the waveguide axis, this condition is fulfilled due to the optical thickness (~ 220 nm) of a high-quality silicon layer. At the same time, the width of such stripe waveguides should be large enough (greater than 10 μm) to provide the acceptable matching with an optical fibre, and hence, these waveguides are necessarily multimode, containing tens of modes.

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In this paper, we describe new heterogeneous SOI waveguides with large transverse dimensions, being at the same time single-mode. A new design of the waveguide structures is based on the production of additionally heavily doped p^+-regions on the sides of a multimode stripe waveguide (the silicon core cross section is ~ 200 nm $\times$ 16 μm). Such doping provides the single-mode behaviour of the heterogeneous waveguide due to the decrease in the optical losses for the fundamental mode and increase in losses for higher-order modes.

Indeed, we can obtain from expressions presented in [3] a simple empirical relation between the achieved change in the real part of the refractive index Δn and additional absorption $\Delta\alpha$ by free charge carriers appearing in this case. For the wavelength 1.55 μm in silicon, this relation for electrons and holes takes the form

$$\begin{aligned} \Delta\alpha_{\mathrm{e}} &= 0.12|\Delta n_{\mathrm{e}}|, \quad \Delta N_{\mathrm{e}} = 1.14 \times 10^{21}|\Delta n_{\mathrm{e}}|, \\ \Delta\alpha_{\mathrm{h}} &= 0.16|\Delta n_{\mathrm{h}}|^{5/4}, \quad \Delta N_{\mathrm{h}} = 2.18 \times 10^{21}|\Delta n_{\mathrm{h}}|^{5/4}, \end{aligned} \tag{1}$$

where ΔN_{h} and ΔN_{e} are the volume concentrations of holes and electrons, respectively; $\Delta\alpha_{\mathrm{e,h}}$ is measured in cm^{-1}, and $\Delta N_{\mathrm{e,h}}$ is measured in cm^{-3}.

It is easy to see from (1) that for $\Delta n_{\mathrm{e,h}} < 0.3$, the control of the optical properties of silicon with the help of free holes is preferable because it provides the same change $\Delta n_{\mathrm{e,h}}$ in the refractive index at lower additional losses. We propose to use p^+-regions for the local control of the optical properties of thin SOI waveguides.

Consider a stripe SOI waveguide of width $W + 2W_{\mathrm{g}}$ with heavily doped p^+-regions of width W_{g} on its sides, where the refractive index is lower than in the waveguide core due to dispersion by free charge carriers. In this way, a heterogeneous optical waveguide is formed (Fig. 1), in which a low-contrast waveguide is added to a multimode high-contrast silicon – oxide waveguide. By selecting $|\Delta n_{\mathrm{h}}| \sim 0.002$ ($\Delta N_{\mathrm{h}} \sim 9.2\times10^{17}$ cm^{-3}, see (1)], we can easily concentrate the main part of the fundamental-mode field energy in the central region of the waveguide of width W, while only a very small part of this energy falls on the dissipative region with charge carriers. The optical fields of all other modes with effective refractive indices close to the refractive index in the doped region or smaller than it occupy the entire cross section of the waveguide. Therefore, the fraction of energy falling on the dissipative region increases by many times (Fig. 1) and a considerable additional decay of optical modes by free

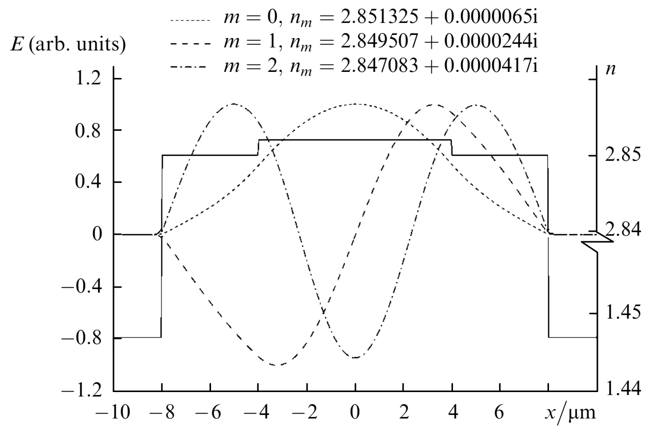

Figure 1. Distribution of the real part of the refractive index n (solid curve) and the optical fields E of the first three modes for heterogeneous stripe waveguides on thin SOI layers for $W = 8$ μm and $W_g = 4$ μm (m is the mode number). The calculation is performed by the two-dimensional BPM.

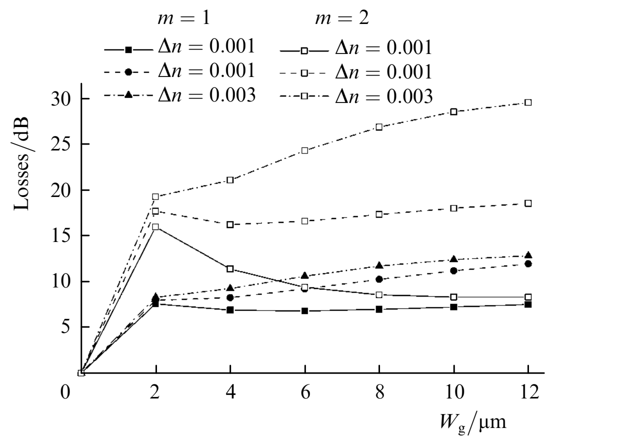

Figure 3. Additional losses by free charge carriers (holes) for the first and second waveguide modes propagating along a heterogeneous optical waveguide of the characteristic length corresponding to optical losses of −3 dB for the fundamental mode as functions of the doped region width W_g.

charge carriers is observed, which increases with increasing mode number.

These general concepts are confirmed by direct calculations by the beam propagation method (BPM) realised by using the commercial BeamPROP software package [4]. In particular, Figure 2 presents the dependences of the additional optical losses by free charge carriers (holes) on the width W_g of doped regions for the three first waveguide modes in heterogeneous optical SOI waveguides. It is easy to see that for the width $W_g \sim 2 - 8$ μm, the efficient selection of the fundamental mode compared to higher-order modes is provided (see also Fig. 3). Therefore, a heterogeneous waveguide with a silicon core of cross section ~ 200 nm $\times$ 16 μm can be made single-mode with optical losses $\sim 1 - 3$ dB cm^{-1}. An additional advantage of the heterogeneous waveguide is that optical losses weakly depend on the degree of roughness of its side boundaries. This is caused both by a large width of the heterogeneous

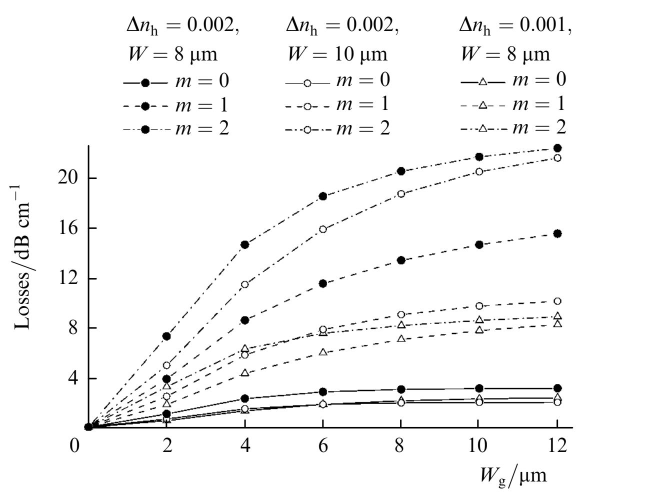

Figure 2. Additional optical losses by free charge carriers (holes) in heterogeneous stripe optical waveguides for different waveguide modes as functions of the width W_g of doped regions for $W = 8$ and 10 μm, $\Delta n_h = 0.002$ and 0.001. The calculation is performed by the two-dimensional BPM.

single-mode waveguide and the isolation of the fundamental-mode field from scattering sources by p^+-regions. For this reason, the optical losses in the heterogeneous waveguide are lower than those in a standard SOI waveguide of a lower cross section (220 × 500 nm) manufactured by the same CMOS technology [1].

Thus, we have proposed a new type of nanophotonic optical SOI waveguides and studied them by the BPM. These waveguides are heterogeneous optical waveguides with heavily doped p^+-regions on the sides of the silicon core (in the form of a stripe of size ~ 200 nm $\times$ 16 μm surrounded by silicon oxide). The additional doping provides the 'single-mode' behaviour of the heterogeneous waveguide due to the decrease in the optical losses for the fundamental mode and increase in losses for higher-order modes (due to the different decay of the optical modes by charge carriers and scattering boundaries of the waveguide.) Heterogeneous waveguides can find applications in silicon nanophotonics.

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