Study of waveguide coupling efficiency in hybrid silicon lasers*

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This paper presents a new method to increase the waveguide coupling efficiency in hybrid silicon lasers. We find that the propagation constant of the InGaAsP emitting layer can be equal to that of the Si resonant layer through improving the design size of the InP waveguide. The coupling power achieves 42% of the total power in the hybrid lasers when the thickness of the bonding layer is 100 nm. Our result is very close to 50% of the total power reported by Intel when the thickness of the thin bonding layer is less than 5 nm. Therefore, our invariable coupling power technique is simpler than Intel's.

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Silicon is the main material in the semiconductor industry and widely applied in microelectronic circuits. Because of the transparency of silicon in the 1.55 μm communication wave band, it is also an important material for photonic integration, so photonic integration on silicon has become a focus of research. To achieve photonic integration, we must exploit active devices based on silicon, such as light sources and detectors. However, because silicon is an indirect band gap material, research on silicon-based light sources has met difficulties.

Many researchers still work on silicon-based light sources, such as the Raman laser [1, 2], LEDs using porous silicon [3], and a hybrid silicon laser [4, 5] reported by Intel, which is a novel and valuable device. The III−V active region and silicon waveguide are bonded together in a hybrid silicon laser. Light emits in the InGaAsP active layer and then couples to the silicon waveguide immediately to select the mode. Part of the light couples to the InGaAsP active layer to emit the same frequency photons, and other light outputs resonate from the silicon waveguide. Thus, a light source based on silicon is obtained.

The emitting efficiency of the laser is related not only to the losses of waveguide, but also to the coupling efficiency of the two waveguides. The coupling efficiency of the two waveguides depends on the thickness of the oxide layer which is generated by bonding. If the process of bonding is perfect, the coupling efficiency will be high, but if not, the thickness of the oxide layer will be large, and it will decrease the coupling efficiency significantly.

The hybrid silicon laser reported by Intel was pumped optically. When the thickness of oxide layer was less than 5 nm, the total maximum output power taking into account the light from both facets and the coupling losses was approximately 28 mW and the corresponding slope efficiency was 16%. However, the thickness of bonding layer less than 5 nm requires strict technical qualifications. For a clean room of one hundred level, the number of granules whose diameters are greater than 0.1 μm is 3459 per cubic foot (FED-STD 209E standard), so a bonding layer less than 5 nm can only be achieved in a black vacuum. Consequently, increasing the thickness of the bonding layer and lowering the difficulty of the technique is a focus in the field and also is the emphasis of this paper.

The structure of the hybrid silicon laser reported by Intel can be simplified to an InP waveguide and a silicon-on-insulator (SOI) waveguide. The InP waveguide consists of a 110 nm-thick InP spacer, a 550 nm-thick InGaAsP emitting layer, and an InP cladding layer. The SOI waveguide consists of an oxide layer generated by bonding, a 500 nm-thick SiO_2 cladding layer, and a Si waveguide with the height (H) and width (W) of 1 μm and 4 μm, respectively. And the bottom is a Si substrate. Fig.1 shows the structure.

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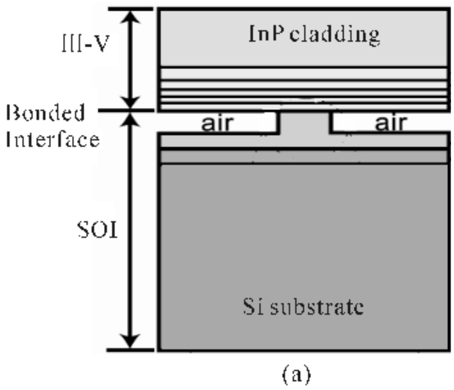

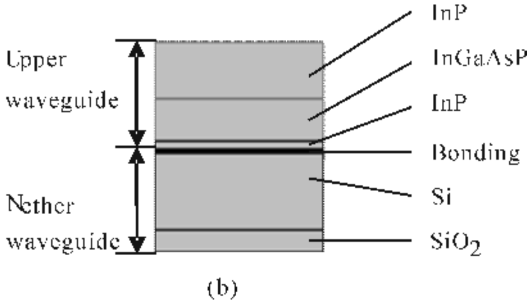

Fig.1 (a)The structure of the hybrid laser;(b)The simple waveguide structure of the hybrid laser.

Supposing that light is imported to the InGaAsP active layer of an InP waveguide and then is coupled to the silicon waveguide immediately, the maximum coupling power can be calculated. Thus, by changing the thickness of the bonding layer, we obtain the maximal coupling power for the silicon waveguide and analyze the effect of the bonding layer thickness on coupling efficiency when the thickness of the InP spacer is 0.11μm and 0.50 μm, as shown in Fig.2.

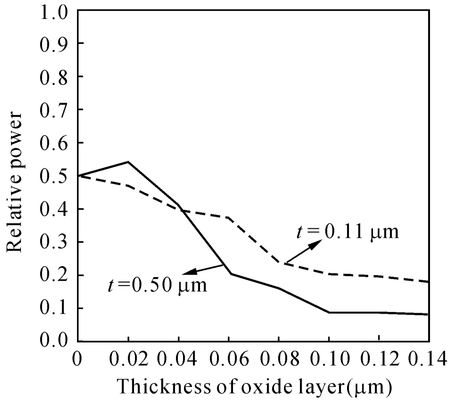

Fig.2 For the Intel′s structure, the effect of the bonding layer thickness on coupling efficiency when the thickness of the InP spacer are 0.11 μm and 0.50 μm,respectively.

Fig.2 shows that when the thickness of the bonding layer is less than 5 nm, the coupling power is about 50% of the total input power. Although the bonding layer is very thin, the coupling power cannot achieve 90% of the total power, because the light propagating with a high loss in the InP waveguide and a silicon waveguide decreases the coupling power. The coupling power decreases as the thickness of the bonding layer increases. When the thickness of the bonding layer is larger than 100 nm, the coupling power is lower than 20% of the total power.

According to the coupled-wave theory [6], the light wave inputs to the InGaAsP active layer, and couples to the relevant parallel waveguide. The powers of the two waveguides can be expressed as,

$$P_1(z) = \cos^2 sz + \frac{\Delta\beta^2}{4s^2}\sin^2(sz), \tag{1}$$

$$P_2(z) = \frac{\kappa^2}{s^2}\sin^2(sz), \tag{2}$$

where $k^2 = s^2 - (\frac{\Delta\beta^2}{2})^2$ and k is the coupling coefficient.

The maximum power conversion between two waveguides requires phase matching ($\Delta\beta = 0$), which indicates that the propagation constant of the InP waveguide must be equal to the propagation constant of the silicon waveguide.

The power of the two waveguides can be simplified as,

$$P_1(z) = \cos^2(\kappa z), \tag{3}$$

$$P_2(z) = \sin^2(\kappa z). \tag{4}$$

A medium waveguide of three layers consists of the substrate, the core region and cover region from top to down, and the responding refractive indices are n_2, n_1 and n_3. For TE mode, the eigenvalue equation is,

$$\mathrm{tg}(hd) = \frac{h(p+q)}{h^2 - pq}, \tag{5}$$

where h *is* the transverse propagation constant, p and q are the transverse decay constants in the substrate and cover regions, respectively. The three constants can be expressed as,

$$h^2 = -\beta^2 + k_0 n_1^2, \tag{6}$$

$$p^2 = \beta^2 - k_0 n_2^2, \tag{7}$$

$$q^2 = \beta^2 - k_0 n_3^2. \tag{8}$$

The waveguide of hybrid laser which we analyzed is simplified to the three-layer structure, when the decay constant p equals to q, TE mode can be divided into even and odd mode, the eigenvalue equation is,

$$\tan\left(\frac{hd}{2}-\frac{m\pi}{2}\right)=\frac{p}{h} \qquad \begin{cases} m=0,2,4,\ldots\ldots & \text{even} \\ m=1,3,5,\ldots\ldots & \text{odd} \end{cases} \tag{9}$$

The propagation of a medium waveguide can be simulated by solving the eigenvalue equation for TE mode, and the propagation constant has a series of discrete values. The propagation constant is related to the thickness of the core region. Thus, we adjust the thickness of the InGaAsP active layer of the InP waveguide to change the propagation of the InP waveguide by setting it equal to the propagation constant of the silicon waveguide. Supposing that the bonding layer is 100 nm, the propagation constants of the silicon waveguide are calculated numerically by Matlab,

β=13.9456, 13.1341, 11.6892, 9.4197, 6.1059, when m = 0, 1, 2, 3, 4.

For the maximum of the coupling power, the propagation constants of the two waveguides must be equal. First, we put a series of β into Eqs.(6)-(8). In accordance with the condition of propagation, h, p and q should be larger than zero, so the propagation constant of the silicon waveguide is 13.1341. Then we calculate that when the InGaAsP active layer is about 0.39 μm, the propagation constants of the two waveguides are equal.

Supposing that light is imported to the InGaAsP active layer of the InP waveguide again and then is coupled to the silicon waveguide immediately, the maximum coupling power can be calculated. Thus, as shown in Fig.3, by changing the thickness of the bonding layer from 0.55 μm to 0.42 μm, we obtain a coupling efficiency which is above 85%.

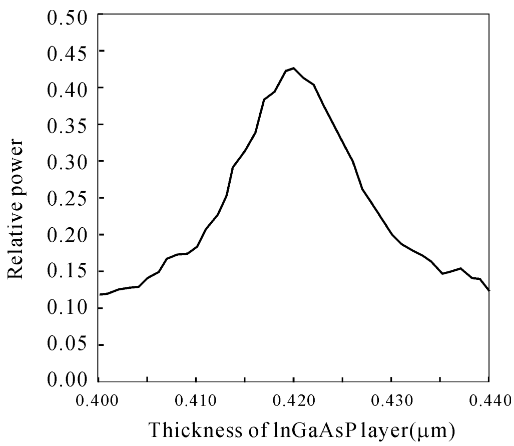

Fig.3 When the bonding layer is 100 nm, the coupling power changes with the thickness of the InGaAsP layer.

Accounting for the loss of the waveguide, the coupling power of the silicon waveguide is 42% of the total power, which is coincident with the result calculated directly.

The change of the spacer also affects the coupling of the waveguides, but the effect of the spacer layer depends on the coupling length of the two waveguides. When the two waveguide are phase matching, the coupling length is

$$L=\frac{\pi}{2\kappa}, \tag{10}$$

where κ is the coupling coefficient in the formula, which has a negative exponential relation with the distance of the two waveguides. The distance of the two waveguides increases with the thickness of the spacer. Thus, the coupling coefficient will decrease, and the coupling length will increase. Therefore, for the hybrid silicon laser, the coupling length should be less than the length of the device (800 μm) and the thickness of the spacer should be smaller than 1 μm.

For the designed waveguide, light is imported to the InGaAsP active layer of InP waveguide, and is coupled to the silicon waveguide immediately. The maximum coupling power can be calculated to judge the magnitude of the coupling efficiency.

Fig.4 shows the effect of the bonding layer thickness on the coupling of waveguides, when the thickness of the spacer is 0.11 μm and 0.50 μm, respectively.

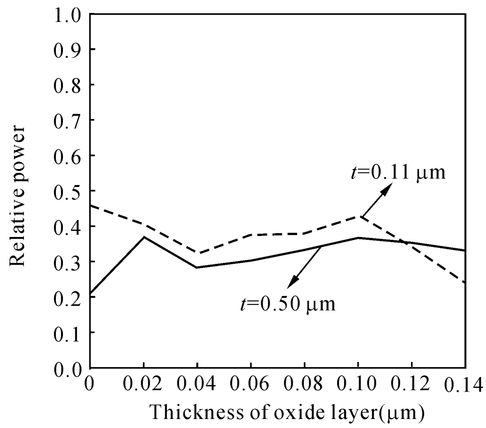

Fig.4 For the designed structure, the effect of the bonding layer thickness on coupling efficiency when the thickness of the InP spacer is 0.11 μm and 0.50 μm.

For the designed structure, as the thickness of the bonding layer changes from 20 nm to 100 nm, the effect on the coupling efficiency weakens, and the change of the coupling efficiency is lower. Thus this design effectively lowers the demands of the thickness of the oxide layer in the bonding process, and reduces the difficulty of the technique.

The coupling power we calculated is very close to the result of Intel. However, the influence of the bonding layer thickness on the coupling power is weakened. The coupling efficiency of the hybrid silicon laser is enhanced effectively by changing the thickness of the active layer of the InP waveguide. To a large extent, the effect of the thickness of the bonding layer on coupling efficiency is improved, so the emitting efficiency of the hybrid silicon laser is effectively enhanced.

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