Effects of Non-abrupt Interface on Waveguide Properties of SiGe/Si MQW Photodetector*

Zhu Yuqing(朱育清), Yang Qinqing(杨沁清) and Wang Qiming(王启明)

(*National Integrated Optoelectronics Laboratory, Institute of Semiconductors, The Chinese Academy of Sciences, Beijing* 100083)

Abstract The formation of non-abrupt interface makes the refractive index profile of an actual SiGe/Si MQW no longer a periodic square wave. A multi-step index mode is proposed to simulate the actual refractive index profile. Based on this mode, the dispersion equation of the MQW waveguide is obtained by using the transfer matrix method. The effects of index change on the optical field and characteristics of photodetector are evaluated by solving the dispersion equation. It shows that the non-abrupt interface results in decreased effective absorption coefficient and quantum efficiency.

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With the development of MBE and MOCVD techniques, the MQW waveguide has become an important structure in some optoelectronic devices[1~3]. SiGe/Si MQW waveguide photodetectors have been demonstrated[3~6]. By using the SiGe/Si MQW structures as natural waveguides, a high quantum efficiency and improved transient performance can be obtained. Generally, the refractive index profile of a MQW guide core is theoretically assumed to be a periodic square wave. However, the actual interfaces of SiGe/Si MQW are not abrupt, and the refractive index profile can be described by the Guassian distribution.

In this paper, a multi-step index mode is proposed to simulate the actual waveguide and evaluate the effect of the index changes on the effective absorption coefficient and quantum efficiency for a practical SiGe/Si MQW photodetector.

Fig. 1(a) shows one period of the index profile of a MQW waveguide, where curve Ⅰ represents the ideal square wave profile, and curve Ⅱ, Ⅲ represent two actual index pro-

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Zhu Yuqing received the B. S. degree in 1991 and M. S. degree in 1994. Since 1994, she has been working toward Ph. D. degree and engaged in research on GeSi PIN photodetectors and GeSi HPT.

Yang Qinqing In 1987, he switched his work to optoelectronic devices. Currently he is working on Si-based optoelectronic devices mainly on SiGe/Si MQW light emission and detector devices, and also interested in SiGe-base HBTs.

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files. The multi-step index profile is used to simulate the actual profile is shown in Fig. 1 (b), where the diffusion region is divided into several small sub-regions with the refractive index n_i and width l_i in sub-region $i(i=1,2,3,\cdots,8)$. It is assumed that the waveguide core contains N periods with period thickness t. n_{c0} and n_{c1} are the refractive index of the cladding layers on both sides of the guide core, respectively. Let n_{eff} be the effective refractive index, $n_i > n_{eff} > n_8, n_{c0}, n_{c1}$ $(i=1,2,\cdots,7)$. The transverse propagation constant in each layer can be expressed as follow[7,8]:

$$Y_{c0} = k_0(n_{eff}^2 - n_{c0}^2)^{1/2}$$
$$Y_i = k_0(n_i^2 - n_{eff}^2)^{1/2} \qquad (i = 1,2,\cdots,7)$$
$$Y_8 = k_0(n_{eff}^2 - n_8^2)^{1/2}$$
$$Y_{c1} = k_0(n_{eff}^2 - n_{c1}^2)^{1/2}$$

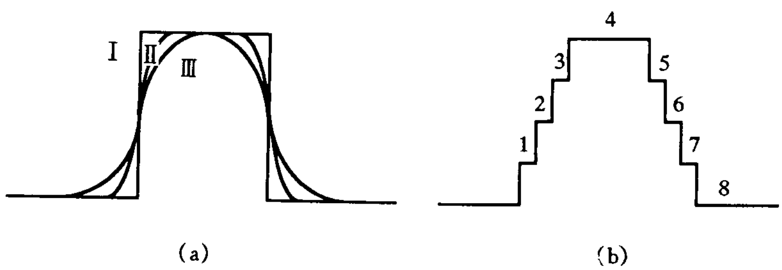

Fig. 1 (a) The refractive index profile of a period of the multiple quantum well optical waveguide. Curve I represents the square wave profile, Curve II and III correspond cases of the Si-Ge interdiffusion;
(b) The multi-step refractive index approach in a period of the multiple quantum well optical waveguide

It is assumed that light propagates in the z direction and there are no field variations in the y direction. The y component of the field distribution in the various layers can be expressed as:

$$\Psi_y(x) = A\exp[-Y_{c0}(x-x_0)] \qquad x < x_0$$
$$\Psi_y(x) = B_i\cos(Y_i[x - (x_0 + nt + \sum_{j=1}^{i-1} l_j)]) + C_i\sin(Y_i[x - (x_0 + nt + \sum_{j=1}^{i-1} l_j)])$$
$$x_0 + nt + \sum_{j=1}^{i-1} l_j < x < x_0 + nt + \sum_{j=1}^{i} l_j \qquad i = 1,2,\cdots,8$$
$$\Psi_y(x) = Ak\exp[-Y_{c1}(x - x_0 - T)] \qquad x > x_0 + T$$

where $n=0,1,2,\cdots,N-1$, and x_0 is the starting point of the waveguide core. A, B_i, C_i and k are the amplitude constants in the respective layers. By applying the boundary conditions at each interface, the mode dispersion equation can be obtained and is expressed as:

$$A_{00} - \frac{1}{\sigma_0}Y_0A_{01} - \frac{\sigma_1}{Y_1}A_{10} + \frac{\sigma_1 Y_0}{\sigma_0 Y_1}A_{11} = 0$$

where A_{00}、A_{01}、A_{10}、A_{11} are expressed as:

$$\begin{pmatrix} A_{00} & A_{01} \\ A_{10} & A_{11} \end{pmatrix} = \left[\prod_{i=1}^{7} \begin{pmatrix} \cos(Y_{8-i}l_{8-i}) & -\frac{\sigma_{8-i}}{Y_{8-i}}\sin(Y_{8-i}l_{8-i}) \\ \frac{Y_{8-i}}{\sigma_{8-i}}\sin(Y_{8-i}l_{8-i}) & \cos(Y_{8-i}l_{8-i}) \end{pmatrix} \begin{pmatrix} \cosh(Y_8 l_8) & -\frac{\sigma_8}{Y_8}\sinh(Y_8 l_8) \\ -\frac{Y_8}{\sigma_8}\sinh(Y_8 l_8) & \cosh(Y_8 l_8) \end{pmatrix} \right]^N$$

$$\prod_{i=1}^{7} \begin{pmatrix} \cos(Y_{8-i}l_{8-i}) & -\frac{\sigma_{8-i}}{Y_{8-i}}\sin(Y_{8-i}l_{8-i}) \\ \frac{Y_{8-i}}{\sigma_{8-i}}\sin(Y_{8-i}l_{8-i}) & \cos(Y_{8-i}l_{8-i}) \end{pmatrix}$$

and $\sigma_i = 1$ for TE mode, $\sigma_i = n_i^2 (i = 1, 2, \cdots, 7, 8$ *and* c_0, c_1 for two cdadding layers) for TM mode.

The expression is a general one, it can also be used to calculate the square wave refractive index profile when all $n_i (i = 1, 2, \cdots, 7)$ are equal to the well refractive index.

By using the dispersion relations presented above, an actual SiGe/Si MQW photodetector is analysed. The calculations are performed at wavelength of 1.3μm. Only the TE mode is considered, since the TM mode result is similar to that of the TE mode. The active layer of the detector used in this work consists of 9 periods of 34nm $Ge_{0.35}Si_{0.65}$ wells and 149nm Si barriers. The sample is grown by MBE at 700℃. The Auger measurement of the sample is shown in Fig. 2. From Fig. 2, it can be seen that the fraction of Ge is higher in the wells near the surface and lower in the inner wells, and the width of the inner wells are wider than that of wells near the surface. The X-ray diffraction measurement also shows that the interfaces between layers are degraded. This may be caused by the Si-Ge interdiffusion and controlling problems during the growth process. The calculated TE mode field based on the refractive index profile in Fig. 2 is given with the solid line in Fig. 3. The field distribution based on the square wave index is also shown with the dot line for comparison. From Fig. 3, it can be seen that the field distribution of the actual waveguide is asymmetric, and its intensity is smaller than that of the ideal case. The peak of the asymmetric distribution moves toward the surface.

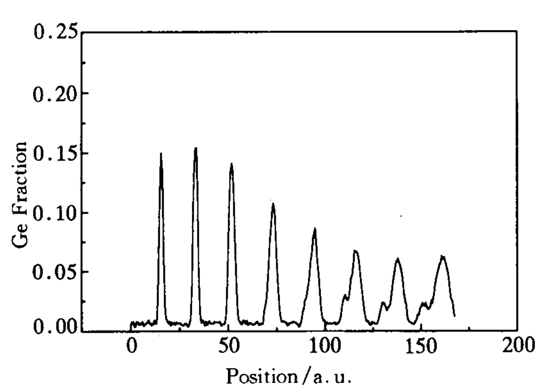

Fig. 2 Plot of Ge fraction as a result Auger measurement

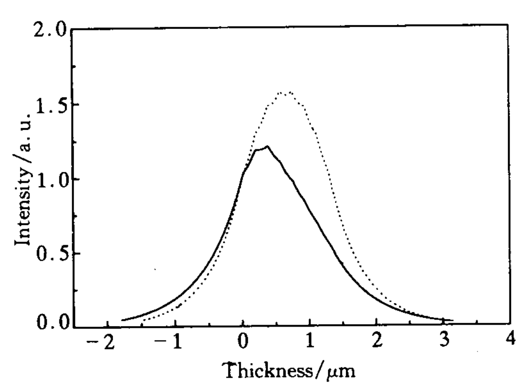

Fig. 3 Plot of the field intensity of actual (solid line) and theoretical (dot line) photodetector for TE_0 mode

The relation between the confine factor Γ and effective absorption coefficient α_{eff} is:

$\alpha_{eff} = r\alpha\Gamma$[3], where r is the percentage of the thickness of absorption layers to the total thickness of the core and α is the absorption coefficient of $Si_{1-x}Ge_x$ alloy. In the case of square wave index profile, the calculation results show that the optical confine factor Γ is 0.835, and the effective absorption coefficient α_{eff} is 17.2 cm^{-1}. However, in the case of actual $Si_{0.65}Ge_{0.35}/Si$ MQW photodetector, Γ is calculated to be 0.772 and α_{eff} is only about 5.47cm^{-1}. It can be seen that although Γ only decreases a little, α_{eff} decreases a lot. This means that the decrease of Γ is one of the reasons of the decrease in α_{eff}. In fact, the decrease of α_{eff} can also be caused by reduction of value r. In the inner wells, the fraction of Ge is very low, their absorption at wavelength of 1.3μm becomes very weak. The effective thickness of absorption layers is reduced and hence the α_{eff}. The quantum efficiency of the device is expressed as:

$$\eta = (1 - R)(1 - e^{-\alpha d})$$

if only the effect of effective absorption coefficient on the quantum efficiency is considered, the reflectivity of the surface and the transmitting depth of light signals are assumed to be unchanged, the ratio of actual quantum efficiency to the theory value is:

$$\frac{\eta_{actual}}{\eta_{theory}} = 0.318$$

It means that the degraded interface is one of reasons reducing the quantum efficiency of the practical device.

In summary, the existence of the Si-Ge interdiffusion and poor control during the growing process of SiGe/Si MQW degraded the interfaces of wells and barriers. The refractive index profile is no longer a periodic square wave. The multi-step refractive index mode has been proposed to simulate the actual waveguides. This approximation is applicable to most MQW structures and useful for future MQW optical waveguide device design and optimization. In this paper, the optical properties of the SiGe/Si MQW waveguide photodetector are calculated. It shows that the non-abrupt interface has undesirable effects on the characteristics of the devices. It decreases the optical confinement and effective absorption coefficient, and results in a low quantum efficiency. To further improve the performance of the device, a thin absorption layer and a low growth temperature, together with good control, must be adopted.

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