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Radiation emission from wrinkled SiGe/SiGe nanostructure

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Semiconductor optical emitters radiate light via band-to-band optical transitions. Here, a different mechanism of radiation emission, which is not related to the energy band of the materials, is proposed. In the case of carriers traveling along a sinusoidal trajectory through a wrinkled nanostructure, radiation was emitted via changes in their velocity in a manner analogous to synchrotron radiation. The radiated frequency of wrinkled SiGe/SiGe nanostructure was found to cover a wide spectrum with radiation power levels of the order of submilliwatts. Thus, this nanostructure can be used as a Si-based optical emitter and it will enable the integration of optoelectronic devices on a wafer. © *2010 American Institute of Physics*. [doi:10.1063/1.3360881]

Semiconductor optical emitters radiate light via band-to-band optical transitions wherein the electrons in the conduction band recombine with the holes in the valence band to emit radiation characterized by the energy bandgap of the material. The emission intensity of IV-IV compounds is relatively weak as compared to III-V compounds owing to the indirectness of the energy band in the momentum space. Since the vast majority of electronic devices are made from Si-based materials, clearly, Si-based optical emitters are in demand for the integration of optoelectronic devices on a wafer. These devices, if realized, would have significant impact on the development of present semiconductor technology.

Here, a radiation mechanism different from the conventional mechanism of conduction-to-valence optical transitions is proposed; this mechanism is based on carriers traveling through a wrinkled nanostructure, which was developed recently.[1–3] Analysis is performed based on wrinkled p-type SiGe/SiGe nanostructure, although the same effect occurs in n-type structures as well. It is found that radiation is emitted via changes in the velocity of the holes, in a manner analogous to synchrotron radiation (electric dipole transitions). The radiated frequency covers a wide spectrum and is characterized by both the periodicity of the wrinkled nanostructure and the velocity of the holes. The radiation power in the infrared region estimated from the physical parameters of a micron-scale p-MOS device with a wrinkle periodicity of 0.1 μm, is of the order of milliwatts. This result indicates that the wrinkled nanostructure can be used as an optical emitter. This study opens different avenues for research on the use of thin films as emission sources, and it is a step toward realizing Si-based optical emitters. Furthermore, such a radiation mechanism applies to III-V and II-VI compounds and the wavelength of emission no longer relies on the band gap of the material provided that a selective etching technique is developed to yield similar patterns of wrinkles.

First, we briefly describe the structure and the characteristics of the wrinkled nanostructure. The structure consists of two thin layers of $Si_{1-x}Ge_x/Si_{1-y}Ge_y$ with different Ge compositions deposited on a Si buffer layer. Both layers are p-type doped and are initially strained because of the lattice mismatch between the Si buffer layer and the bilayer. By removing the Si buffer layer using the standard semiconductor process of selective etching, the bilayer thin film is debonded, resulting in a freestanding film. The freestanding film relaxes through bending and stretching and eventually reaches its equilibrium state, forming a wrinkled pattern. A schematic plot of the pattern is depicted in Fig. 1. The freestanding bilayer film has air between the pattern and the silicon substrate. A detailed description of the fabrication process and formation mechanism of the pattern is reported elsewhere.[1,2] The morphology of the wrinkled pattern is characterized by (a) the displacement in the growth direction $z(x,y)$, and (b) periodicity of the pattern (L_w). The displacement can be expressed as a function of L_w as $z(x,y) = Ag(y/h)\sin kx$, where $k=2\pi/L_w$ is the wrinkle wave number, A and h are the wrinkle amplitude and lateral ething

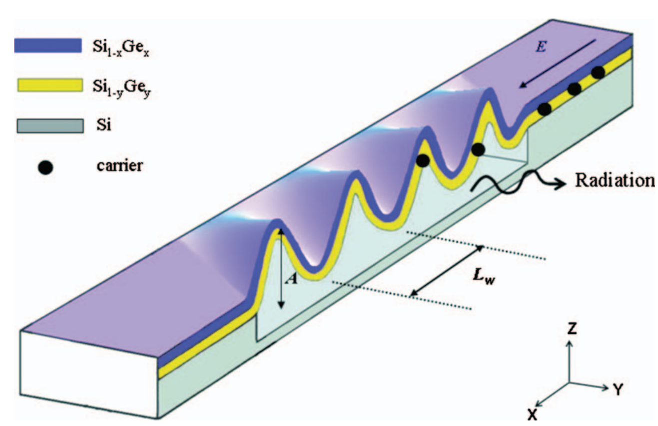

FIG. 1. (Color) Schematic plot of the wrinkled pattern. Holes (solid circle) travel through a sinusoidal trajectory when a voltage is applied across the wrinkled pattern.

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depth. Note that $g(1)=1$ at the free edge (at $y=h$) and $g(0)=0$ in the bonded area.

The carriers (holes) in the bilayer film are initially confined within a triangular potential that is formed at the $Si_{1-x}Ge_x/Si_{1-y}Ge_y$ interface, confined like a two-dimensional hole gas. By placing a metal contact at both ends of the wrinkled pattern, holes travel through the wrinkles when a voltage is applied across the contacts (x-direction) as illustrated in Fig. 1. The velocity of the holes is obtained by differentiating the displacement $z(x,y)$ with respect to time,

$$v_z = Akv_x \cos(kx), \tag{1}$$

where v_z and v_x are the vertical (z) and horizontal (x) projections of the hole velocity, respectively, and follow the condition,

$$v_x^2 + v_z^2 = V_d^2, \tag{2}$$

where V_d is a constant average velocity of holes under the influence of applied electric field.

Substituting Eq. (1) into Eq. (2), we determine v_x and v_z as follows:

$$v_x = \frac{V_d}{\sqrt{1 + A^2k^2 \cos^2 kx}}, \tag{3}$$

$$v_z = \frac{AkV_d \cos kx}{\sqrt{1 + A^2k^2 \cos^2 kx}}. \tag{4}$$

Differentiating Eqs. (1) and (2) with respect to time gives,

$$a_z = Aka_x \cos kx - Ak^2v_x^2 \sin kx, \tag{5}$$

$$v_x a_x + v_z a_z = 0, \tag{6}$$

where a_x and a_z are the horizontal (x) and vertical (z) projections, respectively, of the hole acceleration.

From Eqs. (3), (4), and (6), it follows that,

$$a_x = -Aka_z \cos kx. \tag{7}$$

Substituting Eqs. (3) and (7) into Eq. (5) yields,

$$a_z = -\frac{Ak^2V_d^2 \sin kx}{(1 + A^2k^2 \cos^2 kx)^2}. \tag{8}$$

Equation (8) shows that the hole, while it moves along the free edge of the wrinkled film, undergoes harmonic motion with frequency f given by,

$$f = v_{x,m}/L_w, \tag{9}$$

where $v_{x,m}$ is the mean velocity over a wrinkle period.

Averaging Eq. (3) over the wrinkle wavelength and taking into account that $A^2k^2 \ll 1^1$, we get,

$$v_{x,m} = \frac{V_d}{L_w}\int_0^{L_w} \frac{dx}{\sqrt{1 + A^2k^2 \cos^2 kx}} = \frac{V_d}{2\pi}\int_0^{2\pi}\left(1 - \frac{A^2k^2}{2}\cos^2 \phi\right)d\phi = V_d\left(1 - \frac{A^2k^2}{4}\right). \tag{10}$$

Thus, the oscillating hole radiates a monochromatic wave[4,5] of the frequency,

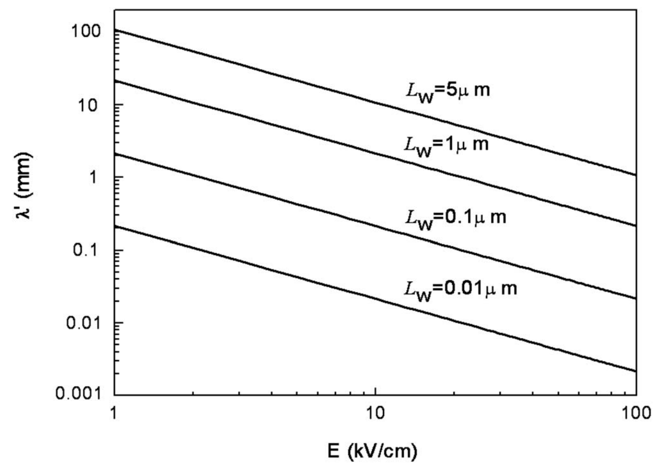

FIG. 2. Emission spectra for different wrinkle periodicities.

$$f = \frac{V_d}{L_w}\left(1 - \frac{A^2k^2}{4}\right). \tag{11}$$

As shown in Refs. 1 and 2, the product A^2k^2 depends weakly on the etching depth and is approximately 0.017. To a good approximation, Eq. (11) can be simplified to yield the frequency and wavelength of the radiation as,

$$f = \frac{V_d}{L_w}, \quad \lambda = \frac{cL_w}{V_d}, \tag{12}$$

where c is the speed of light in vacuum.

In the rest reference frame, the frequency f' and wavelength λ' of the emitted wave depend on (due to the Doppler effect) the viewing direction given by the angle θ,

$$f' = \frac{f}{1-(v_{x,m}/c)\cos\theta} = \frac{(V_d/L_w)}{1-(v_{x,m}/c)\cos\theta},$$

$$\lambda' = L_w\left(\frac{c}{v_{x,m}} - \cos\theta\right). \tag{13}$$

Equation (13) shows that, since $v_{x,m}/c$ is negligibly small, the radiated frequency depends on two factors: (a) the periodicity of the wrinkled pattern as L_w^{-1} and (b) the hole average velocity V_d. With respect to the former factor, as has been shown in Refs. 1, 2, and 6, layers with various L_w can be fabricated. Both the wavelength and amplitude of wrinkles increase with the depth of etching and scale[1,2] as $h^{0.62}$. Further, the hole velocity is proportional to the magnitude of the applied electric field (E) ($V_d=\mu E$, where μ is the hole mobility, and its value depends on the quality of the samples). The radiated frequency for various L_w is calculated as a function of electric field ranging from 1 to 100 kV/cm. The mobility is set to 1400 $cm^2/V\ s$, which was deduced from the average value of the bilayer film of $Si_{0.51}Ge_{0.49}/Si_{0.82}Ge_{0.18}$ reported in Ref. 6, and the mobility of each layer is linearly extrapolated from the bulk values of Si and Ge. These results are plotted in Fig. 2. The spectrum covers a wide range. For large L_w ($\geq 1\ \mu m$), the device emits long wavelengths on the centimeter scale. As L_w decreases, which can be achieved by reducing the lateral etching depth, the emitted wavelength becomes shorter. For $L_w \leq 0.1\ \mu m$, the emitted wavelengths lie mostly in the infrared and visible regions.

Next, the radiation power (P) for the electrical dipole transition is derived. For a single hole following the wrinkled trajectory, P can be estimated using the Larmor formula as[5]

$$P = \frac{q^2 A^2 k^4 V_d^4}{12\pi\varepsilon_0 c^3} = \frac{4}{3}\pi^3 \frac{q^2 A^2 V_d^4}{\varepsilon_0 c^3 L_w^4} = 0.018 \frac{q^2 V_d^4}{\varepsilon_0 c^3 L_w^2}, \quad (14)$$

where q is the carrier charge and ε_0 is the dielectric constant. This shows that the radiation power also depends on the periodicity of the wrinkled pattern as L_w^{-2} and hole velocity as that of radiated frequency. To estimate P under the application of current, we use the physical parameters of a conventional p-MOS device on the micron scale operated at high electrical field, that is, a saturation velocity $V_d = 10^7$ cm/s, current of 1 mA, and $L_w = 0.1$ μm; a reasonable power on the order of submilliwatts is obtained. This demonstrates that the proposed nanostructure can be used as a tangible optical emitter at the infrared region. Note that, by reducing periodicity of the wrinkled nanostructure, not only the radiated frequency shifts toward the visible region as shown in Fig. 2, but radiation power also increases.

This study shows that radiation is emitted by the holes traveling through the wrinkled SiGe/SiGe nanostructure. The mechanism of radiation emission is not related to the indirectness of the energy band and the bandgap of SiGe because the radiation emission depends only on the velocity of holes under an applied field and not on the conduction-to-valence transitions. This mechanism can help remove the main obstacle (indirectness in the energy band) in the use of group IV compounds as emission sources. For a wrinkled nanostructure with a fixed periodicity, the ability to tune the radiated frequency according to the velocity of holes implies that it can radiate light at different frequencies by changing the applied voltage. (The carrier velocity is a function of the applied voltage.) Thus, the proposed nanostructure offers a practical advantage over the conventional optical emitters that emit light with only a single frequency corresponding to the bandgap.

To enable the practical implementation of the proposed nanostructure as optical emitters, we should be able to fabricate them in foundries using the current technology. As these wrinkled structures are fabricated by the standard Si-based processing technique by predefining the periodicity and they are compatible with the present Si-based thin film technology, they can be fabricated on a wafer. For using optical emitters in the energy range of infrared and visible regions, which is desired in many applications, the periodicity of the wrinkled structure should be less than 0.1 μm, as discussed above. This can be easily achieved by reducing the lateral etching depth[2] using the deep submicron technology. Thus, the proposed nanostructure could serve as tangible Si-based optical emitters for the integration of optoelectronic devices on a wafer.

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[1] A. I. Fedorchenko, H.-H. Cheng, V. I. Mashanov, and A.-B. Wang, J. Mech. **21**, 131 (2005).
[2] A. I. Fedorchenko, A.-B. Wang, V. I. Mashanov, W.-P. Huang, and H. H. Cheng, Appl. Phys. Lett. **89**, 043119 (2006).
[3] P. Cendula, S. Kiravittaya, Y. F. Mei, Ch. Deneke, and O. G. Schmidt, Phys. Rev. B **79**, 085429 (2009).
[4] J. R. Tessman and J. T. Finnel, Am. J. Phys. **35**, 523 (1967).
[5] G. Bekefi and A. H. Barret, *Electromagnetic Vibrations, Waves and Radiation* (MIT, Cambridge, MA, 1987).
[6] W.-P. Huang, H. H. Cheng, A. I. Fedorchenko, and A.-B. Wang, Appl. Phys. Lett. **91**, 053103 (2007).