

Comparative Analysis of Pressure Sensors Based on Two-dimensional Photonic Crystals Using Si and GaAs

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Research Article

Keywords: Photonic crystal, Plane wave expansion, Finite difference time domain method etc

Posted Date: February 24th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-218314/v1>

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Version of Record: A version of this preprint was published at Silicon on July 10th, 2021. See the published version at <https://doi.org/10.1007/s12633-021-01246-6>.

Comparative analysis of pressure sensors based on two-dimensional photonic crystals using Si and GaAs

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Abstract — A pressure sensor based on two dimensional photonic crystal structure is presented. The structure considered for sensing is a lattice of air holes surrounded by semiconductor material. A waveguide with central microcavity is formed by filling air holes with semiconductor material. The sensing principle depends upon the shifting of central wavelength of peak towards higher wavelength region when the pressure is raised. The proposed pressure sensor can work in the range 0-5 GPa. Using this structure, two semiconductors, Si and GaAs, have been taken for analysis. It is found that shifting of resonance wavelength with pressure is more pronounced in GaAs than Si. In the dynamic range 0-5 GPa, sensitivity for sensor with Si is estimated as 1.674 nm/GPa while it is 17.00 nm/GPa for sensor with GaAs. The quality factor and figure of merit (FOM) is also found to be higher for GaAs sensor.

1. Introduction

Photonic crystals (PhCs) are orderly structured nanomaterials with periodic dielectrics and characterised by one of the important optical properties of photonic band gaps (PBG) [1]. These materials have wide ranging applications [2-7]. Light propagating through the crystal give rise to photonic band gap in which certain frequencies are prohibited. When defects are inserted in perfect lattices, then localised mode density can be tuned by external perturbation like temperature, pressure etc. [8-12].

Photoelasticity provides an efficient tool in design of a pressure sensor, wherein the stress changes the refractive index of the material and consequently the optical performance of the device is affected [13]. Photoelasticity is related to phenomenon of electrostriction whereby electric fields induce stress within a material. These electrostrictive stresses are related to electric field components by photoelastic constants with fourth power of refractive index, make high refractive index materials such as Si and GaAs significantly important for optomechanical application [14, 15]. In addition to this, radiation losses can also be reduced using high refractive index materials [16].

In this work, two dimensional photonic crystal (2D PhC) based pressure sensor is designed with a waveguide and a microcavity in PhC consisting of a triangular lattice of air holes. A comparative study of Si and GaAs is presented to test the performance of the device formed for pressure sensing. The sensing principle is based on the shift of resonance wavelength, which occurs due to the change in refractive index (RI) of material due to the application of

hydrostatic pressure onto the sensing surface [3,7]. The sensitivity, quality factor (Q-factor) and figure of merit (FOM) have been estimated.

2. Numerical Method and Structure

Fig. 1 shows the proposed structure of pressure sensor. It consists of a triangular lattice of air holes in semiconductor slab (Si or GaAs). The distance between two adjacent hole (lattice constant, a) is 400 nm and the radius r of air holes is $0.37a$. The waveguide is obtained by removing one row of air holes in X direction and, a microcavity is obtained at the centre of wave guide by removing two air holes in Z direction. The microcavity is separated from waveguide with two holes on either sides of cavity as shown in Fig. 1.

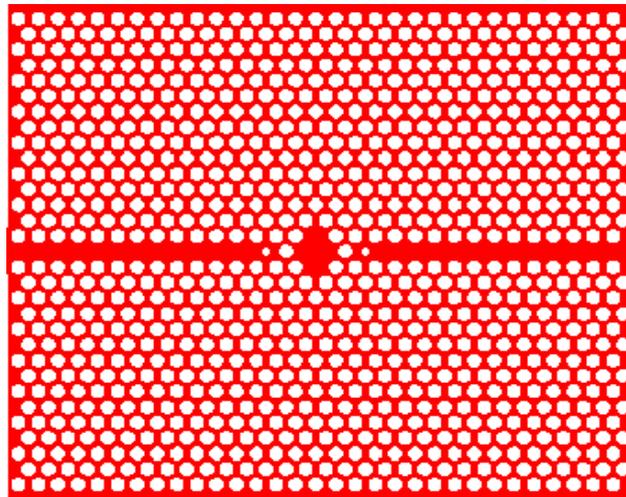
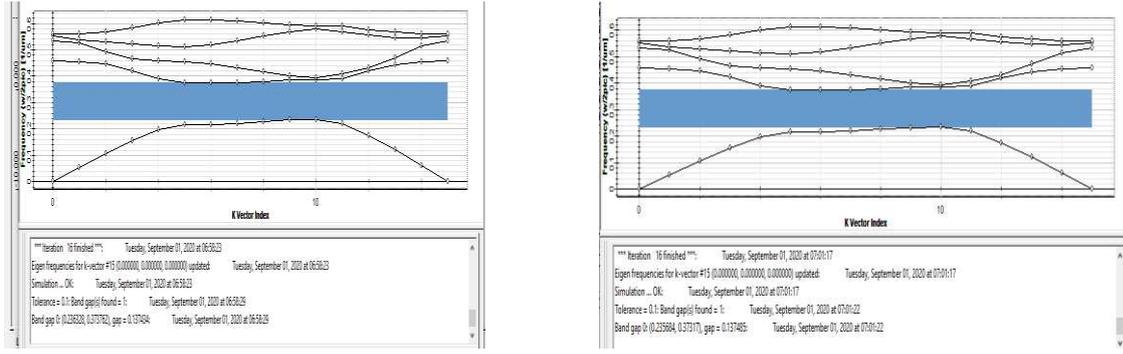


Fig. 1. Schematic diagram of PhC based sensor

By employing plane wave expansion method (PWEM), dispersion curves for regular structure are obtained. The regular PhC structure (without defect) with Si ($n_{Si}=3.42$) has a band gap (PBG) for TM modes in a range 1060.44 nm to 1739.88 nm in normalised frequency units ($\omega a/2\pi$) b/w 0.2299 a/λ to 0.3772 a/λ . Similarly, the structure for GaAs slab material ($n_{GaAs}=3.43$) has a PBG in the range 1062.98 nm to 1744.43 nm for normalised frequency units ($\omega a/2\pi$) b/w 0.2293 a/λ to 0.3763 a/λ . Band structure diagrams for Si and GaAs are shown in Fig. 2. In above range of PBG, no wavelength is allowed to propagate in photonic crystal. The localization of light can be obtained in the range of PBG by introducing defect in the structure.



a)

b)

Fig. 2. Structure of TM mode band gap: a) Si ; b) GaAs

In this work, waveguide in the 2D photonic crystal are studied by a finite-difference time domain (FDTD) method [17]. We have used computational domain of 31x31 lattice constants (total 961 unit cells). Each unit cell contains 441 (21x21) discretization grid points for the FDTD time-stepping formula. The computation domain is surrounded by perfectly matched layer (PML). The total number of time steps is taken 50,000 with each time step $\Delta t = 0.99/c \sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2}}$, where c is the speed of light, Δx and Δy are space intervals of size 5 nm.

3. 2-D Photonic Crystal Pressure Sensing

The pressure sensor is formed using a triangular lattice of air holes in slab of Si or GaAs. The number of holes in X and Z direction is 31×31. The incident source is a Gauss impulse light with a wave length of 1550 nm (which is a standard for optical communications) located at the input of the waveguide and the detector is placed at the end of the waveguide.

The optical sensor based on photonic crystal is based on the variation of the refractive index with the parameters like temperature (thermo-optic effect), pressure (photo-elastic effect) etc. When the external pressure is applied on a surface of the sensor, the refractive index of the material will be changed due to stress applied. This variation allows the change in the photonic band gap as well as shifts in the resonant wavelength. Due to the photo-elastic effect, the refractive index of medium change with the stress/stain. Using photo-elastic effect and stress-strain relation, the relation between the refractive index and stress in a tensor form is taken as [18]

$$\Delta\left(\frac{1}{n^2}\right) = \sum p_{ij} \sigma_j \quad (1)$$

n is refractive index, p_{ij} are strain-optic coefficients and σ_j is stress component.

Assuming that the medium is isotropic and the pressure is applied only in one direction, the pressure modified refractive index has the simplified equation [3, 19]

$$n = n_0 - (c_1 + 2c_2) \sigma \quad (2)$$

Where c_1 and c_2 are defined as

$$c_1 = \frac{n_0^3(p_{11} - 2V p_{12})}{2E} \quad (3)$$

$$c_2 = \frac{n_0^3[p_{11} - V(p_{11} - p_{12})]}{2E} \quad (4)$$

Where n_0 is refractive index of material at zero pressure, p_{11} and p_{12} are strain optic coefficients, E is Young's modulus and V is Poisson's ratio [19].

4. Results and Discussion

When photonic bandgap of uniform structure is calculated it is found that PBG of GaAs structure (681.45 nm) is slightly larger than PBG of Si structure (679.44 nm). This is expected as the refractive index of GaAs is higher than Si. Basically, PBG structure depends not only upon refractive index but also on lattice constant and radius to lattice constant ratio (r/a) [20]. Primary band gaps of 2d Phc structures depend on the refractive index contrast and air-filling fraction (the ratio of air to total volume in the structure). Even for certain values of air-filling fractions, increasing the index contrast may reduce the size of the fundamental band gap, or make them virtually disappear [21]. In this work, radius to lattice constant ratio is taken as $r/a = 0.37$, which provides higher width of PBG for higher refractive index contrast of GaAs.

In transmission curves, a resonance peak is observed in photonic band gap. The effect of changing the radius of smaller holes in waveguide, r_1 (shown in Fig 1) is studied on central wavelength, quality factor and transmission of the peak. The transmission spectrum is shifted as radius of holes is increased. Quality factor increases and transmission first varied slowly than decreases with radius r_1 as shown in Table 1. In our analysis for sensing pressure, radius of small holes is taken $r_1 = 0.180 a$. ($T > 0.8$, $Q > 200$).

Table 1 Variation of resonance peak with radius of hole

r_1	Si			GaAs		
	Central wavelength(nm)	Quality factor	Transmission (T)	Central wavelength(nm)	Quality Factor	Transmission (T)
0	1545	64.53	0.8311	1549	65.07	0.8296
0.074 a	1548	76.70	0.8363	1552	77.76	0.8398
0.148 a	1549	131.27	0.8342	1553	133.14	0.8380
0.222 a	1545	338.81	0.7553	1550	337.54	0.7491
0.296 a	1543	411.57	0.4868	1547	409.69	0.4806
0.37 a	1538	429.48	0.2611	1542	427.97	0.2568

We find linear relations between refractive index and applied pressure by eq (2). Pressure produces stress and strain in material. The strain-induced change of absorption coefficient or

energy band gap are considered as the main cause of the significant change of refractive index [22, 23].

The variation of wavelength of resonance peak with applied pressure is linear for Si and GaAs in accordance with the linear change of refractive index with pressure as shown in Fig.3. By applying the pressure, refractive index of material and geometrical shape of Phc changes as a result PBG structure and resonance wavelength of peak in PBG is shifted [20] and this property can be exploited for measuring the pressure through the sensor.

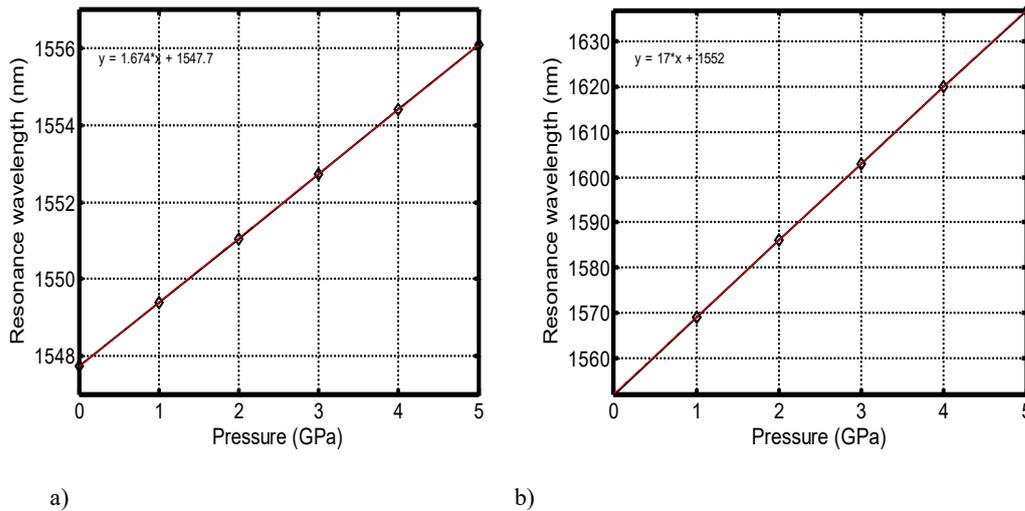
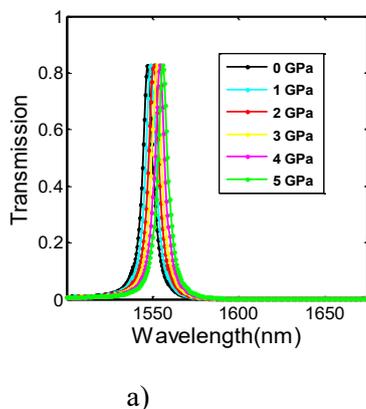
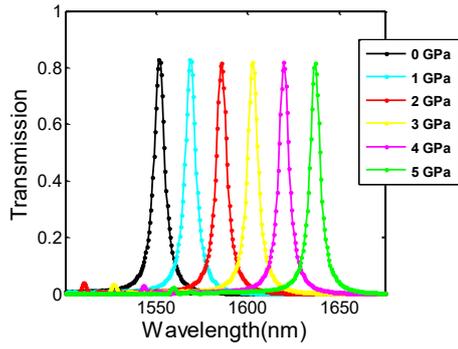


Fig. 3. Pressure vs resonance wavelength: a) Si ; b) GaAs

It is found that for Si, localised mode wavelength or resonant wavelength is located at 1547.72 nm corresponding to 0 GPa. As the pressure on the surface of the structure increases from 0 to 5 GPa, refractive index of Si also increases and wavelength of resonance peak shifts to higher wavelength. For GaAs, localised mode wavelength of the structure is obtained at wavelength 1552 nm corresponding to 0 GPa and shifted to longer wavelength with applied pressure. Normalised transmission spectra for the structure are shown in Fig 4.



a)



b)

Fig. 4. Normalised transmission : a) Si ; b) GaAs

By changing the pressure from zero to 5 GPa, total wavelength shift for GaAs is observed as 85 nm, which is higher than total wavelength shift of Si as 8.37 nm. It is noticed that while increasing the pressure by 1 GPa, the refractive index of Si around 0.0041 is increased. But due to large photoelastic coefficients of GaAs it is observed that refractive index of GaAs increases by 0.0397 with a increased pressure of 1 GPa which is much higher than change of refractive index in Si material. Therefore, GaAs exhibits more wavelength shifts than Si.

The sensitivity S is defined as the ratio between the shift of resonant wavelength ($\Delta\lambda$) induced by the change of applied hydrostatic pressure ΔP [3]

$$S = \frac{\Delta\lambda}{\Delta P} \quad (5)$$

Sensitivity of proposed structure for Si is 1.674 nm/GPa which is much less than the sensitivity of GaAs as 17.00 nm/GPa. Comparing with previously reported 2 D PhCs pressure sensor work which have sensitivity of 11.7 nm/GPa [24], 13.9 nm/GPa [25] and 15.8 nm/GPa[10], our sensor using GaAs structure have higher sensitivity of 17.0 nm/ GPa.

The important performance index for an optical sensor is quality factor that defines the shape of resonant peaks which is expressed by [26]

$$Q = \frac{\lambda}{FWHM} \quad (6)$$

Where λ is the resonant wavelength and FWHM is full width at half maximum.

It is found that quality factor increases with applied pressure. Improvement of Q indicates the better confinement of optical field and reduced radiation losses into the cavity [16]. Average Q factor of proposed structure for Si is estimated as 226.48 whereas the Q - factor, for GaAs is slightly higher as 239.53.

Performance of a sensor can also be described by a parameter such as figure of merit. The figure of merit (FOM), is a numerical expression that is used to characterise the device and defined as [11,27]

$$\text{FOM} = \frac{S \cdot Q}{\lambda} \quad (7)$$

where, S is sensitivity, Q is quality factor and λ is central wavelength. The calculated value of FOM of proposed structure for Si and GaAs are 0.2442 and 2.5528 respectively. So, FOM for GaAs is better than that for Si.

The variation of refractive index, localised mode wavelength (LMW), Q- factor, wavelength shift (WS) and FOM with pressure for Si and GaAs are displayed in Table 2

Table 2 Variation of simulation parameters in Si and GaAs

Level of pressure (GPa)	Si					GaAs				
	N	LMW(nm)	WS(nm)	Q	FOM	n	LMW(nm)	WS(nm)	Q	FOM
0	3.4200	1547.72	0	224.30	0.2426	3.4300	1552	0	226.40	2.4798
1	3.4241	1549.38	1.66	225.52	0.2436	3.4697	1569	17	232.82	2.5225
2	3.4282	1551.05	3.33	226.26	0.2441	3.5093	1586	34	235.20	2.5210
3	3.4322	1552.73	5.01	227.04	0.2447	3.5490	1603	51	242.03	2.5667
4	3.4363	1554.40	6.68	227.55	0.2450	3.5886	1620	68	247.97	2.6021
5	3.4404	1556.09	8.37	228.23	0.2455	3.6283	1637	85	252.77	2.6249

One can understand the expected results of pressure sensor in terms of the difference in the physical and optical properties of Si and GaAs [28]. Si is an indirect bandgap semiconductor with a diamond structure while GaAs is a direct bandgap semiconductor with zincblende structure. This leads to a greater electronic bandgap for GaAs compared to Si. Also for optical processes, Si requires phonon absorption or emission, i.e. the efficiency of the any device that can be formed will be effectively reduced compared to GaAs. Due to the larger resistivity of GaAs compared to Si, the presence of large number of localized states leads to more refractive index changes and hence the larger shifts in the resonance wavelength. This consequently gives a better sensitivity to the GaAs pressure sensor compared to Si.

5 Conclusions

2D PhCs based pressure sensor is presented. The sensor is formed by creating a line and a point defect in air hole structure. Using two semiconductor materials, the effect of pressure on shifting of resonance wavelength of structure is studied and different performance index of sensor are compared. It is found that the sensitivity, Q-factor and FOM of the sensor using GaAs is higher than Si material. This sensor is simulated for the pressure b/w 0 to 5 GPa.

Fundings No source of funding

Conflicts of interest No conflicts of interest

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Figures

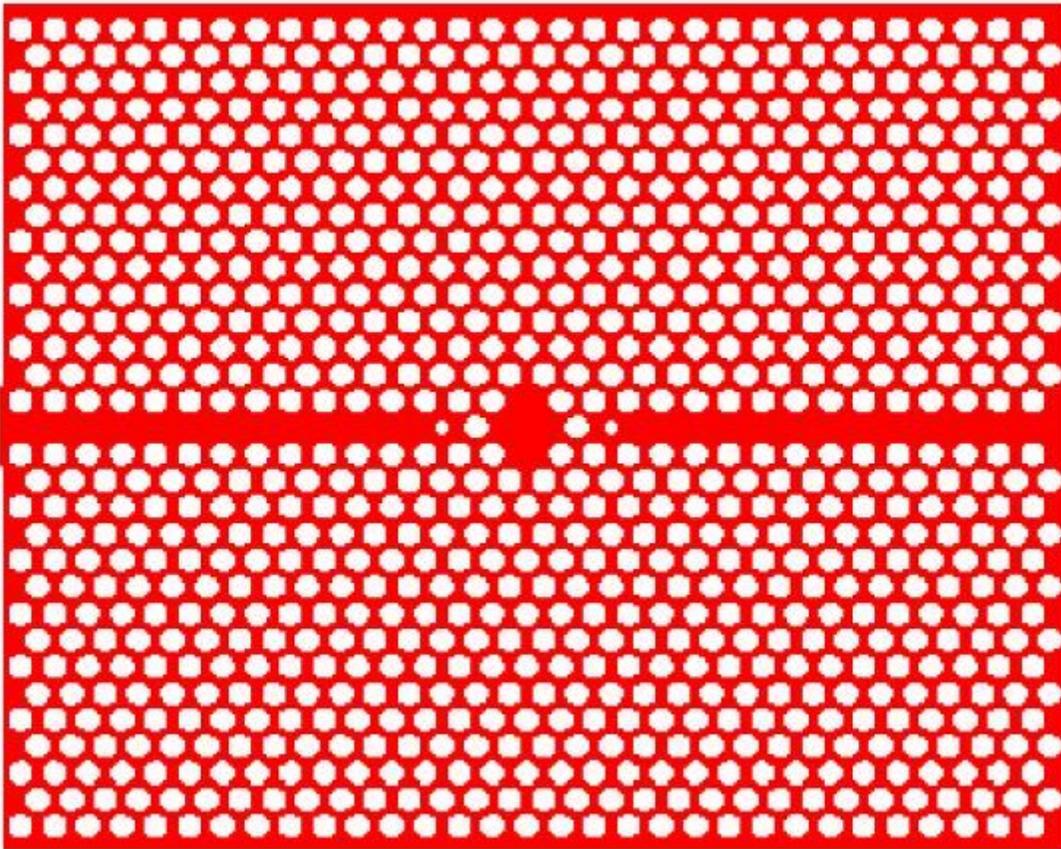
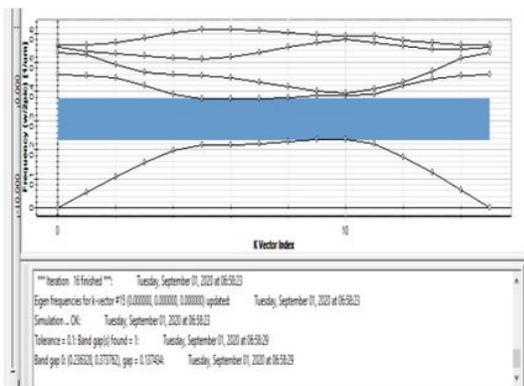
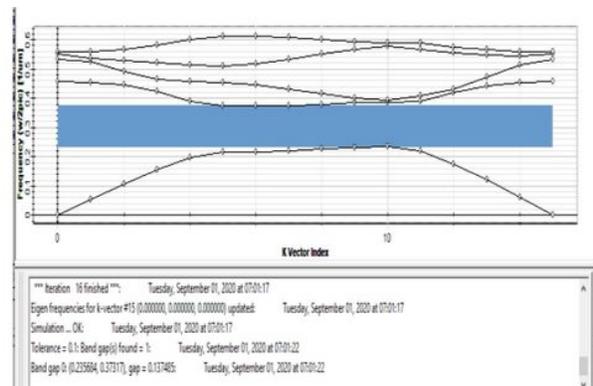


Figure 1

Schematic diagram of PhC based sensor



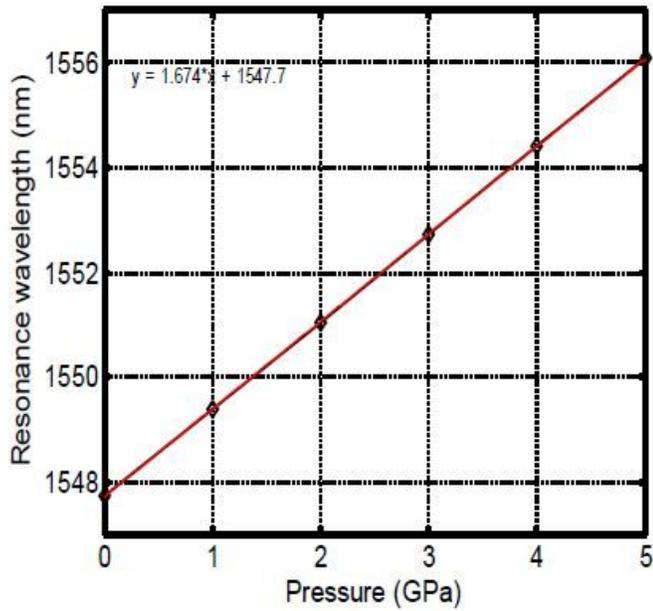
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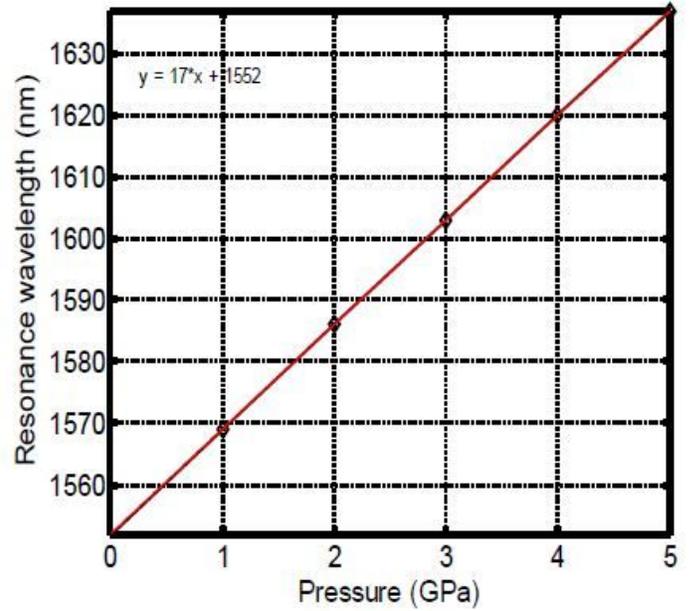
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Figure 2

Structure of TM mode band gap: a) Si ; b) GaAs



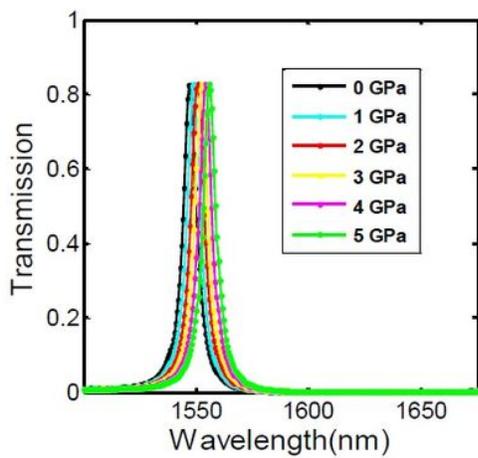
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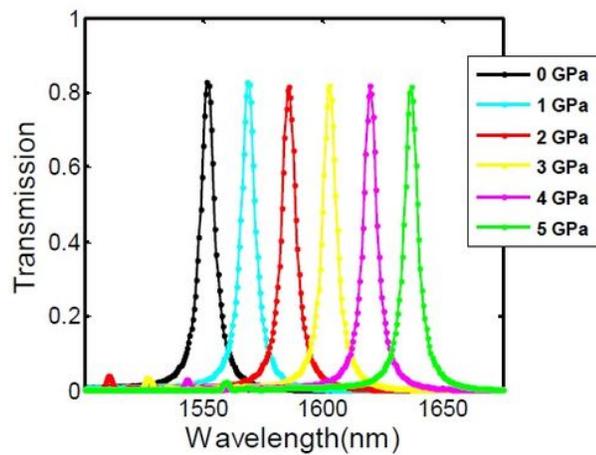
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Figure 3

Pressure vs resonance wavelength: a) Si ; b) GaAs



a)



b)

Figure 4

Normalised transmission : a) Si ; b) GaAs