China Petroleum Processing and Petrochemical Technology

Catalyst Research Volume 23, Issue 2, September 2023 Pp. 1589-1598

CHARACTERIZING ACOUSTIC PROPERTIES USING THE EFFECTIVE MEDIUM MODEL FOR POROUS SILICON AND POROUS SILICON TREATED WITH POLYMER

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ABSTRACT

Porous materials exhibit distinctive and adaptable features that have drawn substantial attention across a variety of scientific and technical areas. They are characterized by their complex internal structures filled with holes or pores. Porous silicon, among these materials, stands out as a particularly fascinating substance due to its exceptional structural and physical characteristics. Porous silicon is a good contender for a variety of applications because of its peculiar porosity, which can be controlled through production procedures. In several disciplines, including acoustics, telecommunications, and material science, acoustic qualities, such as sound transmission, attenuation, and reflection, are crucial. The creation of novel acoustic devices, sensors, and acoustic metamaterials with specialized features depends on our ability to understand the acoustic behavior of porous materials, particularly porous silicon. Additionally, the addition of polymers to porous silicon structures adds a new level of material engineering that may improve or change its acoustic properties. These two materials combined have a lot of potential for use in acoustics and other fields.

This study intends to look into the acoustic characteristics of porous silicon and determine how polymer treatment affects these characteristics. We want to characterize the acoustic behavior of porous silicon and its interaction with different polymer materials by utilizing the effective medium model. In doing so, we hope to add to the expanding body of knowledge about the acoustic characteristics of porous materials and offer insightful information that can guide the creation of cutting-edge acoustic technologies.

Keywords: Porous Silicon (PS), Polymers treated porous silicon, Acoustic Property, Etching time, PMMA & PVC Concentrations, Effective medium model

1. INTRODUCTION

1.1 Acoustic Property:

Among the most challenging characterization techniques of thin films, coating and bulk materials are ultrasonic nondestructive evaluation methods, involving the measurements of wave velocities. The acoustic parameters such as transverse, longitudinal and Rayleigh velocities (VT, VL and VR, respectively), longitudinal impedance, transverse impedance (ZL, ZT) and elastic constants can be investigated through the following relation. The porosity determines the acoustic velocities v and density ρ in the sample, which together determine the acoustic impedance Z = ρv.

The relationship between these acoustic parameters of c-Si and those of p-Si is

A = A0(1-P)m (1)

where A0 is the non-porous acoustic parameter representing: VLo, VTo, VRo, ZLo and ZTo [1-8]. The values of empirical constant m are typical of each individual acoustic parameter. (m: 1.004 - Rayleigh mode, 1.086 - TA , 1.083 – LA, 19.7 – ZL and 13.6 ZT).

1.2 Effective Medium Model:

The PS model is an isotropic two-component system, i.e., a silicon carcass and pores with the dimensions much less than the light wavelength λ. Consequently, PS can be treated as an optically isotropic medium with an effective refractive index n. Its n, which is a function of porosity, is higher than that of air and lower than that of silicon. We consider layers with a low extinction coefficient when the imaginary part of the complex refractive index can be Neglected. The two-component Bruggeman model is known to be in agreement with the experimental data for PS layers on low resistivity p+□Si substrates [9-14]. This kind of model is based on additivity of contribution from each phase into effective polarizability of the medium. The Bruggeman equation for the two-component system is

$$f\left(\frac{(n_{si})^2 - n^2}{(n_{si})^2 + 2n^2}\right) + P\left(\frac{1 - n^2}{1 + 2n^2}\right) = 0 \qquad (2)$$

where n is the effective refractive index of PS, P is the volume fraction of pores;
f =1–P is the silicon volume fraction in porous layers.

Let us imagine that the PS composition has oxidised. Also PS impregnated polymer can be described as a four-component medium, consisting of silicon, oxide, pores and polymers. Here f points out that the silicon volume fraction, and Pin = 1– f, points out that the pore fraction. Pin is porosity prior of PS pores filling with polymers, For the new composition of the film, Si fraction is f, polymers fraction is γ, pore fraction is P = 1– f – γ. The Bruggeman equation for PS impregnated polymer can be written as

$$(fF+YG+(1-f-v)V=0 \qquad (3)$$

From the above equation, we can obtain the Polymer fraction y:

$$Y=[fF+(1-f)V / V-G] \qquad (4)$$

2. RESULT AND DISCUSSION

2.1 Acoustic Properties

The calculated values of acoustic velocity, impedances as well as the density for PS are illustrated in Fig 2&3. By comparing the results with c-Si, the calculated values are lower in PS sample. It can be seen from the Fig. 1 that the percentage of porosity determine the density of the PS. The measured density is found to be decreased (1.334 to 0.414 g/cm3) with an increase the current density. Among the three modes of acoustic velocity, the longitudinal velocity (VL) is found to be higher in the range 4674.92 m/s to 1316.56 m/s with increase the current density. The transverse velocity (VT) and Rayleigh velocity (VR) are similar (3240.48 m/s to 909.39 m/s and 2982.81 m/s to 921.37 m/s) for all the samples. By comparing the impedance values of PS, the longitudinal impedance (ZL) is slightly higher (10.9209 – 3.0755 Pa. s/m) than the transverse impedance (ZT) (7.5269 – 2.1123 Pa. s/m), From the results, the both acoustic velocities and impedance are found to be decreased with increase of current densities as related to the percentage of porosities of PS samples. The pore formation occurring in the next layer (125 mA/cm2 for 30 min in current density or 100 mA/cm2 for 40 min in etching time) is clearly revealed in this analysis also. The acoustic velocities and impedance results reflect the sequence of optical and elastic properties of PS. The similar trends of results are proving for PS with different etching time. While in the case of polymers treated PS (Figs. 8-15), the density of PMMA is found in the range of 0.1863 – 0.2815 g/cm3 for the three different concentrations. Similarly, density in PVC (0.211 – 0.3187 g/cm3), PVP (0.1656 – 0.2815 g/cm3) and Polystyrene (0.1532 – 0.2114 g/cm3) are increase with its concentrations. The results reflected in longitudinal and transverse velocity and impedance (ZL and ZT) of the samples. It means the VL, VT, ZL and ZT are increased with its concentrations. Among the four polymers, the PMMA and PVC showed similar the both velocities and impedance values while the remaining two polymers showed similar acoustic parameters. This result absolutely coincides with the SEM analysis. It is clear from the theoretical results that the optical, elastic and acoustical properties of PS are mainly depends on the percentage of porosity and types of polymers and percentage of concentrations. As established in the experimental studies that (SEM, AFM and PL), the occurrence of pore formation in the next layer (at 125 mA/cm2 for 30 min) is reflected well in the theoretical results. Hence, it is concluded that the theoretical calculation is a simple way to confirm the experimental results.

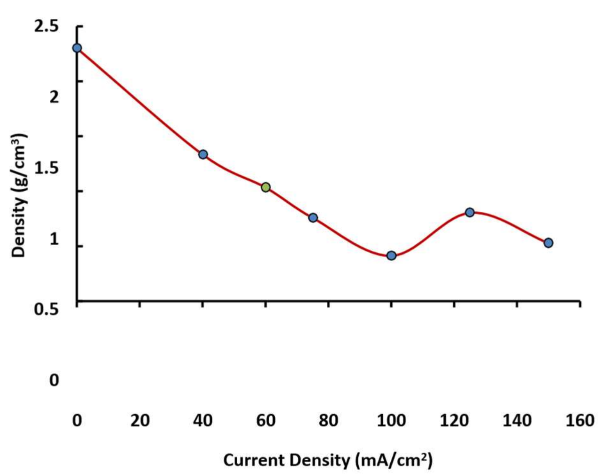

Fig. 1. Variation of density with current density.

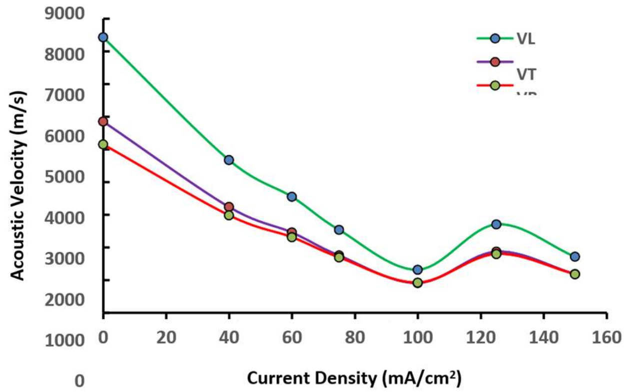

Fig. 2. Variation of Acoustic velocity with current density.

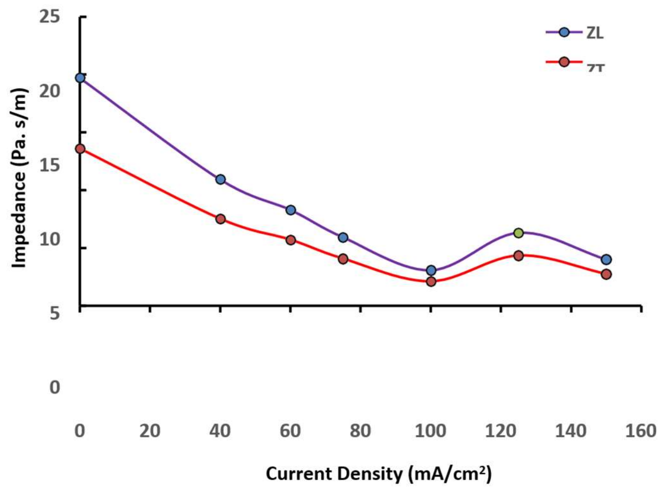

Fig. 3. Variation of impedance with current density.

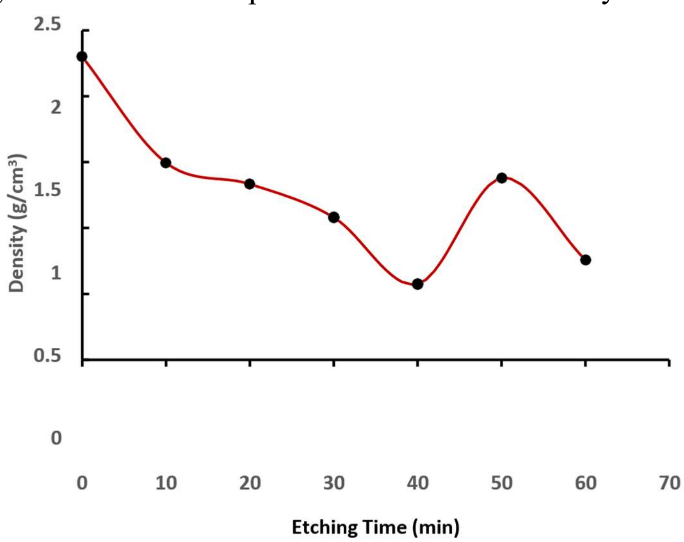

Fig. 4. Variation of density with etching time.

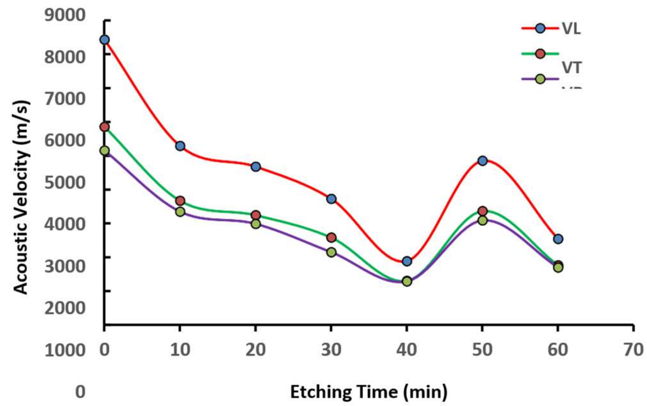

Fig. 5. Variation of acoustic velocity with etching time.

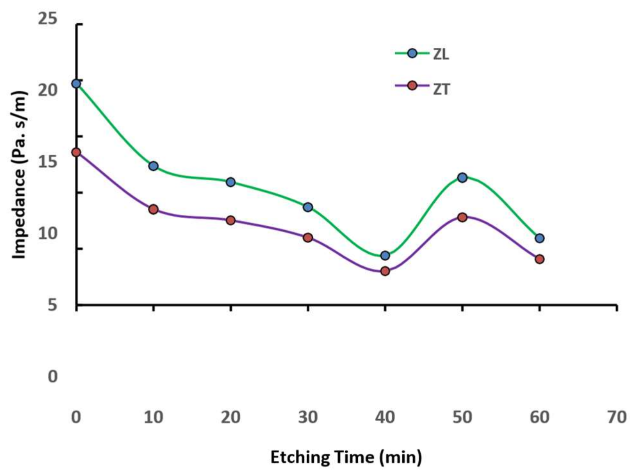

Fig. 6. Variation of impedance in etching time.

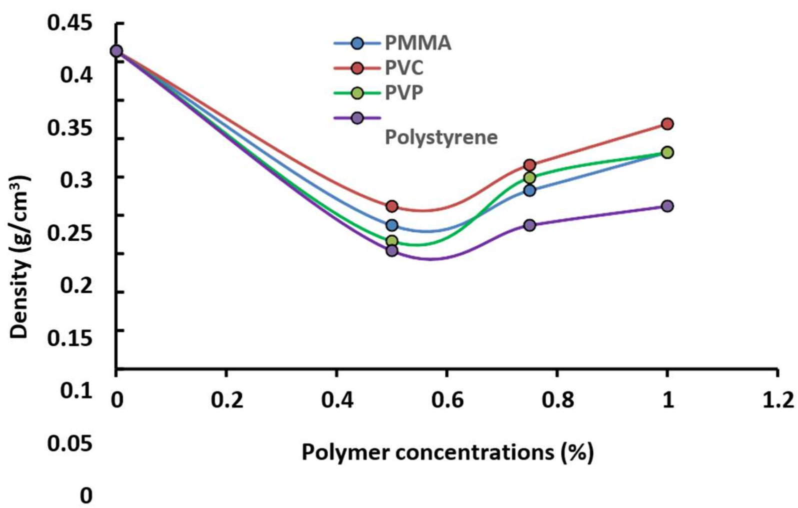

Fig. 7. Variation of density with polymer concentrations.

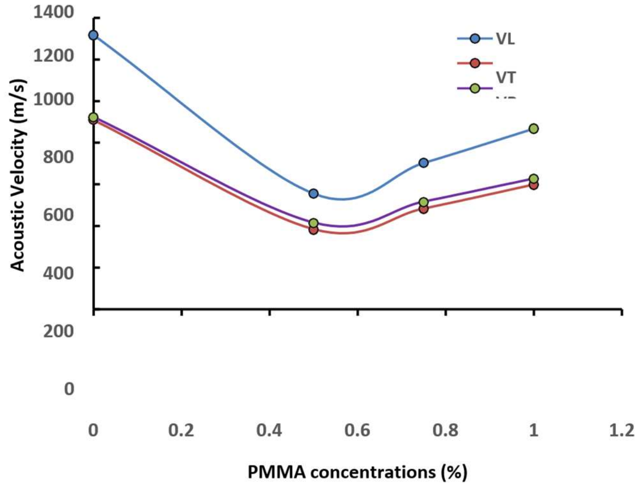

Fig. 8. Variation of Acoustic velocity with PMMA concentrations.

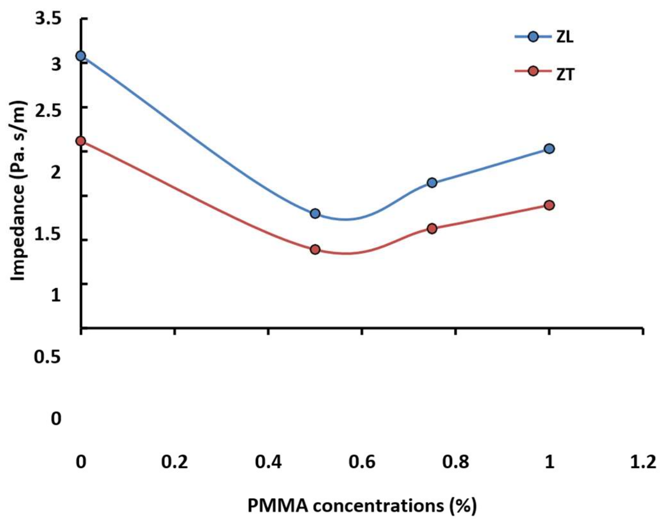

Fig. 9. Variation of impedance with PMMA concentrations.

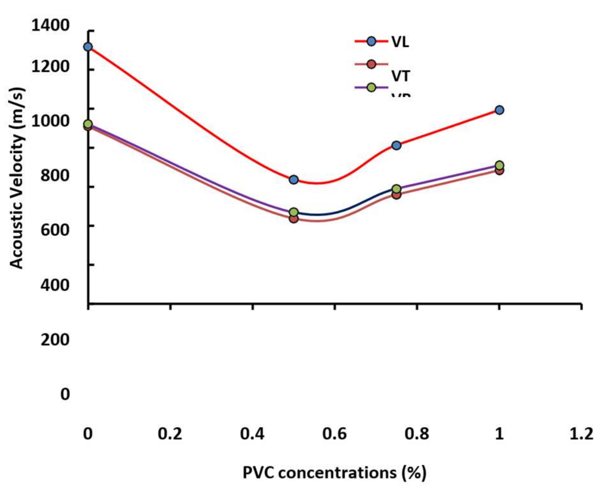

Fig. 10. Variation of Acoustic velocity with PVC concentrations.

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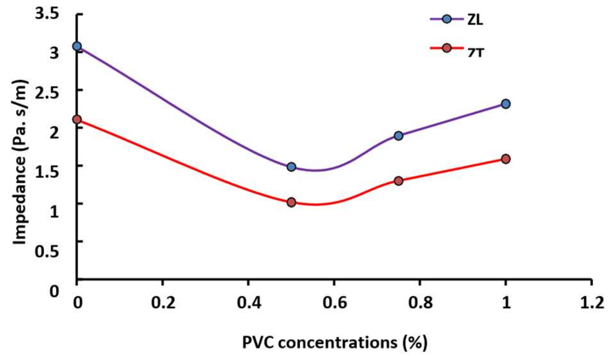

Fig. 11. Variation of impedance with PVC concentrations.

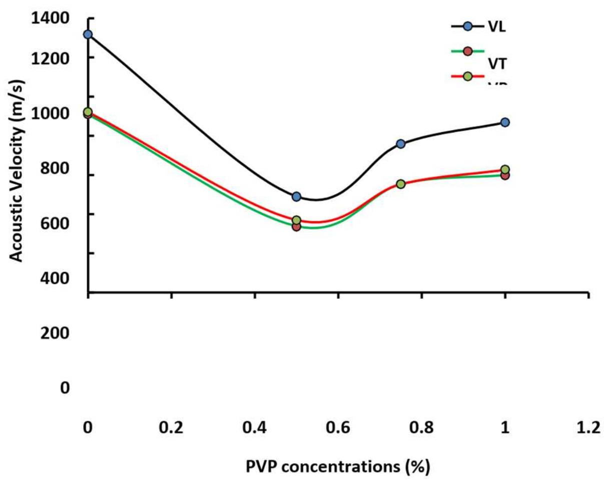

Fig. 12. Variation of Acoustic velocity with PVP concentrations.

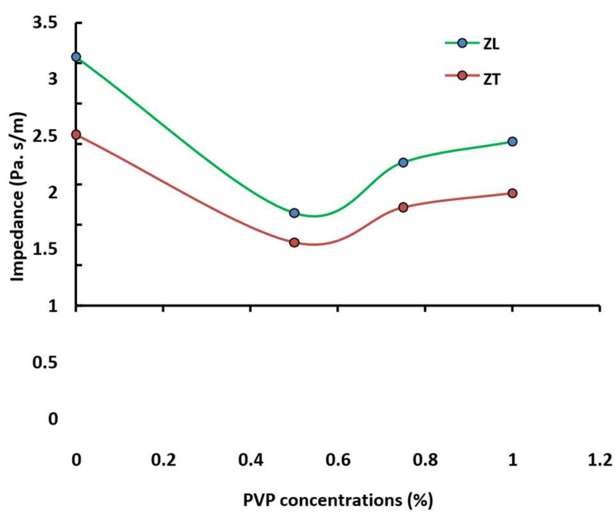

Fig. 13. Variation of impedance with PVP concentrations.

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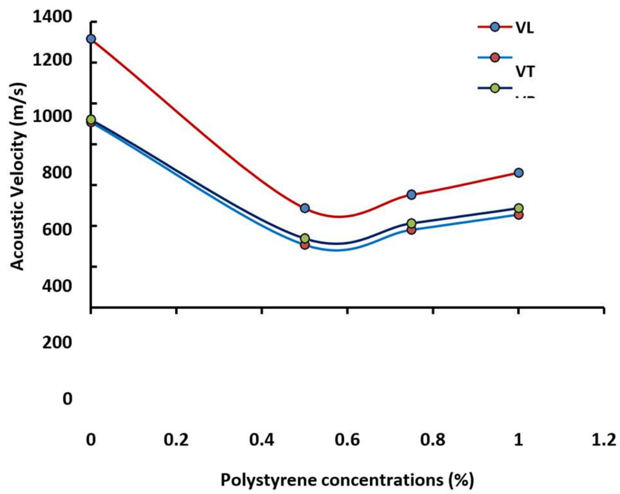

Fig. 14. Variation of Acoustic velocity with Polystyrene concentrations.

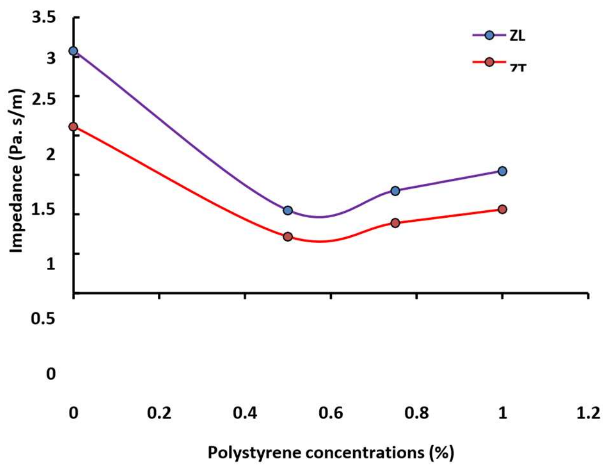

Fig. 15. Variation of impedance with Polystyrene concentrations.

2.2 Effective Medium Model

When polymers are coated on the PS surface, the pores were covered with a very thin layer of the polymers. The polymer fraction values have been estimated for polymer impregnated PS. Increasing the concentration of polymer deposited on the PS layer, the pores were covered with thick layer of polymer and correspondingly the porosity was decreased (Fig. 4-7). By comparing the polymer treated PS, the Polyestrene polymer is more impregnated than PMMA, PVC and PVP. The reason for more impregnation of PVC may be due to its higher viscosity. The SEM studies have indicated that in the case of as-formed porous silicon, uniform pore walls have been formed; however, in the case of polymer impregnated PS, the pore walls were diffused and spreading in the pore region. The calculated values of the effective refractive index of various polymer fractions of PMMA/PS & PVP/PS and also it demonstrates that polymers / PS composite films on the polymer fraction inserted in the pores of porous silicon increases effective refractive index n. Similar results have been reported by Jia, [18] using the four – components Bruggeman approaches

[15-17]. Jia, has also pointed out that his values are lower than the experimental values for higher porosities.

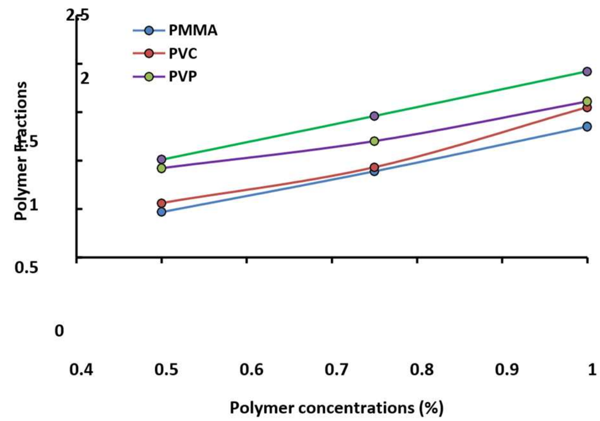

Fig. 16. Variation of polymer fractions with polymer concentrations.

3. CONCLUSION

In summary, this comprehensive study has provided valuable insights into the acoustic properties of porous silicon (PS) and its complex interactions with various factors. Compared to crystalline silicon (c-Si), PS consistently exhibits lower values for acoustic velocity, impedance, and density, underscoring the significant role of porosity in shaping these properties. The density of PS is intricately linked to its porosity, with a pronounced decrease in density observed as current density increases, ranging from 1.334 to 0.414 g/cm³. Among the three modes of acoustic velocity, longitudinal velocity (VL) displays the most substantial variation with increasing current density, while transverse velocity (VT) and Rayleigh velocity (VR) remain relatively stable across all samples. Longitudinal impedance (ZL) slightly surpasses transverse impedance (ZT) in PS, with both velocity and impedance values decreasing as current density rises, consistent with the percentage of porosity.

The presence of pores, notably under specific current density and etching time conditions, is evident in the acoustic properties analysis, aligning with findings from SEM, AFM, and PL analyses, further reinforcing the connection between porosity and acoustic behavior. In the case of polymer-treated PS, different polymers and their concentrations exert a significant influence, with PMMA and PVC showing similar acoustic parameters, including density, longitudinal and transverse velocities, and impedance values, while the other two polymers exhibit similar acoustic behaviors. These results align with SEM analyses, underlining the role of polymer types and concentrations in shaping acoustic properties. Theoretical calculations effectively validate these experimental findings, providing a straightforward means to corroborate the results, particularly in establishing the relationship between porosity, polymer treatment, and acoustic properties.

In conclusion, our study emphasizes the multifaceted impact of porosity, current density, and polymer treatments on the optical, elastic, and acoustic properties of porous silicon. These insights hold practical significance for the development of novel acoustic materials and devices and underscore the importance of theoretical calculations in validating experimental observations.

Furthermore, when polymers are applied to the surface of porous silicon, they form a thin layer covering the pores. The extent of polymer impregnation varies with polymer concentration, resulting in thicker polymer layers and reduced porosity as concentrations increase. Polystyrene exhibits the highest impregnation, likely due to its higher viscosity. SEM studies reveal that while as-formed porous silicon displays uniform pore walls, polymer-impregnated PS exhibits diffused and spreading pore walls within the pore region. Additionally, effective refractive index values were calculated for various polymer fractions in PMMA/PS and PVP/PS composites, indicating that the presence of polymers within porous silicon pores increases the effective refractive index (n). These findings align with previous research employing the four-component Bruggeman approach, as reported by Jia [18]. Importantly, these results suggest that effective refractive index values for higher porosities may be lower than experimental values, further enhancing our understanding of polymer-porous silicon interactions with potential applications in optics and composite materials.

4. REFERENCES

1. Aliev, G.N., Goller, B., and, M. Hashim, H. Abu Hassan, J. Optoelectron. Advan. Mater. 10 (2008) 2653.
2. Da Fonseca, R.J.M., Saurel, J.M., Foucaran, S., Camassel, J., Massone, E., Taliercio, T., and Boumaiza, Y., J. Mater. Sci., 30 (1995) 35 – 39.
3. N.M. Balzaretti, J.A.H. da Jornada, Solid State Commun. 99 (1996) 943.
4. O.M. Khalid, N. Ali, Z. Hassan7991.
5. Lam, P.K., Cohen, M.L., and Martinez, G., Phys. Rev. B, 35 (1987) 9190 – 9194.
6. Al-Douri, Y., Abid, H., and Aourag, H., Physica B, 305 (2001) 186 – 190.
7. Weber, M.J., Handbook of Optical Materials, Vol. 62, Boca Raton, FL: CRC Press, 2003.
8. Gray, P.R., Hurst, P.J., Lewis, S.H., and Meyer, R.G., Analysis and Design of Analog Integrated Circuits, 5th Ed., New York; Wiley, 2009.
9. R.K. Pandey. J. Phys. Chem. Solids. 59 (1998) 1157.
10. Q. He, Z-T. Yan, Phys. Stat. Sol. (b) 223 (2001) 767.
11. J.C. Phillips, Bonds and Bands in Semiconductors, Academic Press. San Diego, 1973.
12. W.A. Harison, Electronic Structure and the Properties of Solids, General Publishing Company, Toronto, 1973.
13. M.L. Choen. Phys. Rev. B, 32 (1985) 7988.
14. P.K. Lam, M, L. Cohen, G. Martinez. Phys. Rev. B, 35 (1987) 9190.
15. D.A.G. Bruggeman, Ann. Phys. (Leipzig). 34 (1935) 636.
16. J.C.M. Garnett, Phil. Trans. R. Soc. Lond. 203 (1904) 385.
17. H. Looyenga, Physica 31 (1965) 401.
18. Z. Jia, Chinese Optics Lett. 3 (2005) 608-610.