

## APPLICATION OF NOVEL MATERIAL IN CRYSTAL ACCELERATOR CONCEPTS

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Materials which incorporate regular macroscopic features superposed on the underlying crystal lattice are of potential interest in the application to crystal accelerators and coherent radiation sources. We have recently begun an investigation of one such material, porous Si, in which pores of radii up to a few tens of lattice spacings are etched through finite volumes of a single crystal. The potential reduction of losses to particles hyperchanneled along the pores makes this a very interesting material in crystal accelerators for relativistic, positively charged particles. Our results on material properties which are important in this context will be presented. The consequences for particle transport will be discussed.

### Introduction

The successful demonstration and theoretical understanding of the phenomenon of the channeling of beams of charged particles along axes and planes of symmetry in crystalline solids<sup>1</sup> has led several investigators<sup>2-7</sup> to suggest the possibility of schemes for accelerating particles in which the lattice fields would play the role of the magnetic transport in conventional accelerators. A significant obstacle to be overcome is the dissipative processes to which a beam of charged particles is subjected in penetrating a solid. For positive particles, the channeling process itself provides a significant reduction. In this case, multiple scattering on the nuclei can be neglected; however that on the electrons, while reduced for channeled particles, is important. In this paper, we will use results we have obtained elsewhere<sup>8</sup> to evaluate the emittance growth of the beam. Then, we describe our research, just now getting under way, to investigate the possibility of exploiting porous Si in this application as a means to further reduce the dissipation.

### Crystal Accelerator Transport

We have recently undertaken an investigation of charged particle transport in crystals in the context of the application of crystalline solids in particle acceleration. This includes both crystal accelerator concepts<sup>2-7</sup> as well as beam "optics."<sup>9</sup> In the case of strong acceleration of heavy particles  $m \geq m_p$ , we have found the following expressions for the mean square radius, mean square angle and rms emittance<sup>8</sup>

$$\begin{aligned} \langle r^2 \rangle &= \frac{D}{\alpha k} \left[ \left( \frac{\alpha z + p_0}{p_0} \right)^{1/2} - 1 \right] \\ \langle \theta^2 \rangle &= \frac{D}{\alpha (\alpha z + p_0)} \left[ \left( \frac{\alpha z + p_0}{p_0} \right)^{1/2} - 1 \right] \\ \varepsilon &= 4 \left( \langle x^2 \rangle \langle \theta^2 \rangle \right)^{1/2} = \frac{4D}{\alpha \sqrt{k}} \left[ \frac{1}{\sqrt{p_0}} - \frac{1}{\sqrt{\alpha z + p_0}} \right], \end{aligned}$$

where  $z$  is the distance of propagation into the crystal,  $\alpha = eE/m_I c^2$ , the accelerating field normalized to the incident particle rest energy,  $p_0$  is the initial momentum normalized to  $m_I c$ ,

and  $k = v_0/m_I c^2$ ,  $v_0$  is the "spring constant of the harmonic channel well. Its specific form depends on the model used to construct the continuum potential of a string of atoms.<sup>1</sup> For our purposes it suffices to take a typical value of  $2 \times 10^{16} \text{eV/m}^2$ .  $D$  is the multiple scattering velocity space "diffusion" coefficient. We have used<sup>10</sup>

$$D = z \pi r_E^2 N Z_{\text{val}} \left( \frac{m_e}{m_I} \right)^2 L_R,$$

where  $r_E$  is the classical electron radius,  $Z_{\text{val}}$  is the number of valence electrons, and  $N$  is the number density of the crystal. Logarithmic dependencies on particle energy have been neglected throughout;  $L_R$  is a constant with a typical value  $\approx 10$ .

Even an ambitious accelerating gradient of 100 GeV/cm taking, for example, a 1 TeV proton to 100 TeV in  $z = 10^3 \text{cm}$ , will leave a  $\delta$ -function beam with an rms emittance  $\varepsilon \approx 5 \times 10^{-12} \text{rad/cm}$ .

This is somewhat larger than the channel acceptance,<sup>3</sup> and dechanneling would be expected to occur, even for this extreme case. It should be noted that the harmonic well approximation is becoming suspect in this case. However, if anything, it would be expected to be too optimistic. The consequences of the multiple scattering increase as the accelerating gradient decrease. Therefore, the possibility of reducing the multiple scattering while maintaining crystallinity and channeling is of interest. It might also be so in other applications, for example, beam steering and focussing or perhaps radiative cooling of light particles using channeling radiation.

### Porous Si Studies

In an attempt to develop materials with properties compatible with theoretical predictions for solid state accelerators, we have initiated an investigation of porous silicon. Numerous papers have been published on porous silicon and the possible applications to device technology<sup>11-16</sup> or as high quality filters.<sup>7</sup> To date we are not aware of any investigation of this materials with respect to applications in accelerator technology. It has been shown in these previous studies that (1) the diameter of the pores can be controlled, (2) the pores can be made perpendicular to the surface of the silicon substrate, and (3) the porous silicon has a crystalline structure with a lattice constant larger than that of crystalline silicon. It is not well understood how straight the pores are or to what maximum length the pores can be made to penetrate into the substrate. The structure of the material in the neighborhood of the pore edge is not well known. This certainly will impact the channeling properties of the pores. Because the pore diameter corresponds to about four unit cells, it is reasonable to speculate the potential well might be very flat, rising sharply near the pore edge. However, the work to be described shows there is a complex, time-dependent chemistry which takes place in the pores. Much more work is needed to understand the properties of this material important in our applications. Theoretical

models will undoubtedly need to be refined as a consequence.

Using an anodizing process, on *p*-type (boron doped) bulk, single crystal silicon, we have initiated a process to produce porous silicon samples. The electrolyte is composed of 50% HF acid and 50% ethanol with current densities in the range of 80 mA/cm<sup>2</sup>. Samples that have been produced by this method have been investigated using infrared Fourier transform spectroscopy.

Figure 1 is the absorbance spectrum at room temperature for a *p*-type silicon reference sample in the spectral range 400 to 5000 cm<sup>-1</sup>. The data were taken using a Bomem DA3.01

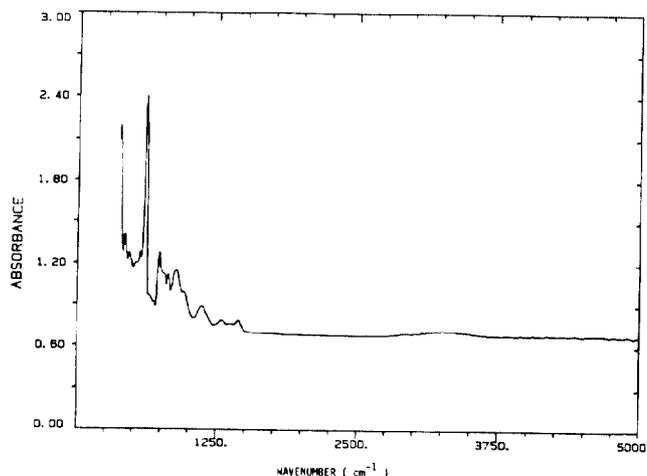


Figure 1: Room temperature absorbance of *p*-type silicon.

Fourier transform infrared spectrophotometer fitted with a mercury cadmium telluride (MCT) detector and KBr beam-splitter. Comparison of Fig. 2 which is a spectrum for slightly anodized (porous) silicon, to Fig. 1 reveals several new features in the spectral region near 2100 and 2900 cm<sup>-1</sup>. These features

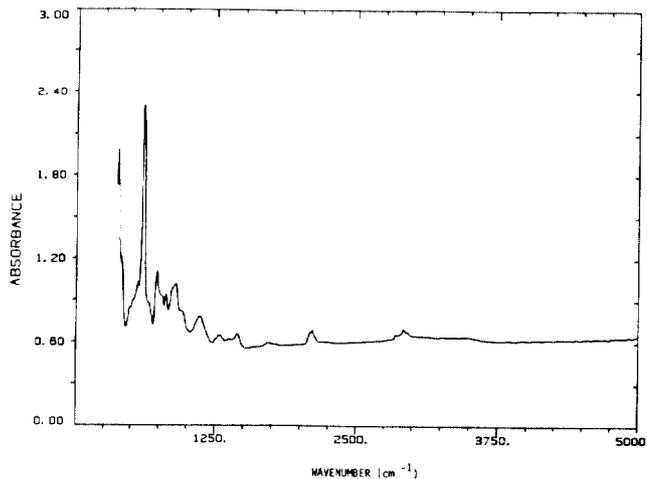


Figure 2: Slightly anodized *p*-type silicon at room temperature.

are believed to be related to oxide (Si-O<sub>2</sub>) formation at the anodized surface and to Si-H vibrational modes, respectively. The spectrum for a 100 μ thick sample of porous silicon is shown in Fig. 3. This sample was provided by the electrical engineering

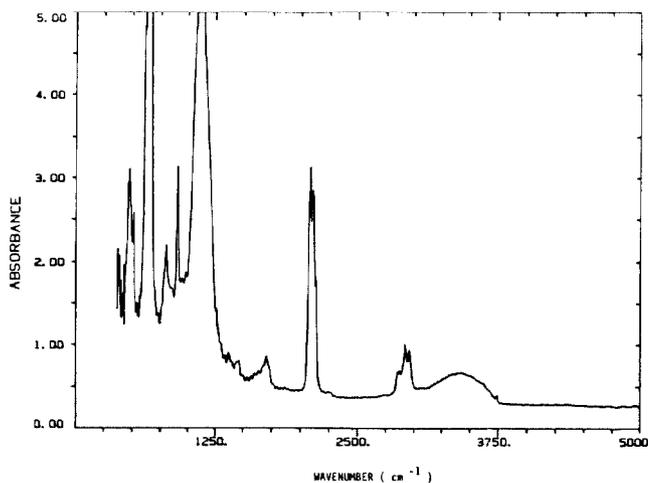


Figure 3: Absorbance of 100 μ thick sample of porous silicon at room temperature.

department of Texas A&M University. It contains pores which have an average diameter of 20 Å. Similarities between the thick porous sample and the slightly anodized sample can be seen in the regions near 2100 and 2900 cm<sup>-1</sup>. At wavelengths larger than 2100 cm<sup>-1</sup> the expected silicon phonon spectrum is completely covered by the multitude of absorption peaks occurring in this region. Again, these peaks are attributed to oxides such as Si-O<sub>2</sub> and to Si-H complexes which have formed in the pores. The time-dependent behavior of this long wavelength absorption is shown in Fig. 4. It is clear that the complexes

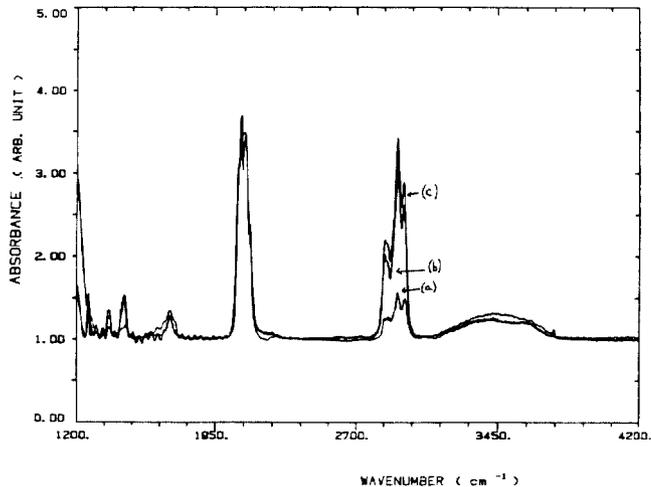


Figure 4: Time-dependent absorbance of 100 μ thick sample of porous silicon (a) 1 day, (b) 14 days, and (c) 28 days after anodizing.

responsible for the absorption continue to form for an extended period of time after the anodization process is complete.

Currently, we are investigating the effects of various annealing temperatures and different atmospheres on the formation of the complexes and have plans to use proton channeling experiments to measure the straightness of the pores.

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