Quasimetallic silicon micromachined photonic crystals

B. Temelkuran, a) Mehmet Bayindir, b) and E. Ozbay
Department of Physics, Bilkent University, Bilkent 06533 Ankara, Turkey
J. P. Kavanaugh, M. M. Sigalas, and G. Tuttle
Ames Laboratory and Microelectronics Research Center, Iowa State University, Ames, Iowa 50011

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We report on fabrication of a layer-by-layer photonic crystal using highly doped silicon wafers processed by semiconductor micromachining techniques. The crystals, built using (100) silicon wafers, resulted in an upper stop band edge at 100 GHz. The transmission and defect characteristics of these structures were found to be analogous to metallic photonic crystals. We also investigated the effect of doping concentration on the defect characteristics. The experimental results agree well with predictions of the transfer matrix method simulations. © 2001 American Institute of Physics.

Photonic crystals are periodic structures that can reflect electromagnetic (EM) waves in all directions within a certain frequency range. These structures can be used to control and manipulate the behavior of EM waves.1,2 Although earlier work concentrated on building these crystals with dielectric materials3,4 there are certain advantages of introducing metals to photonic crystals.5–11

Various techniques have been reported for the fabrication of dielectric layer-by-layer photonic crystals at different frequency regions,4,12,13 and recently at optical frequencies.14,15 However, limitations of the standard machining techniques used to fabricate three-dimensional (3D) metallic photonic crystals restricted experimental demonstrations and technological applications of these crystals to microwave frequencies.9,16 3D metallic structures standing on dielectric supports operating at infrared wavelengths were also demonstrated17,18 However, these structures do not have the advantage of a band gap extending to zero frequency due to nontouching metallic layers. The fabrication of 3D metallic photonic crystals at higher (compared to microwave) frequency regions with a complete metallicity gap extending to zero frequency is still a challenge.

In this letter, we propose a method for the fabrication of layer-by-layer photonic crystals having metallic properties using silicon micromachining techniques. The touching layers form a continuous network, in which the long wavelengths cannot penetrate the conducting mesh, and the band gap extends to zero frequency. We have previously investigated the properties of such a metallic photonic crystal with an upper band edge at 20 GHz. The method allows the fabrication of these structures at a frequency range extending from 100 GHz to 10 THz.

The layer-by-layer photonic crystal was fabricated using highly doped silicon (100) wafers, which were 75 mm in diameter and 400 μm thick. We predicted that, due to the low resistivity of the Si wafers (in the range of 0.0015–0.004 Ω cm), this structure would show metallic photonic crystal properties. We used anisotropic etching of silicon by aqueous potassium hydroxide (KOH) in forming the layers of the quasimetallic photonic crystal. In the first step of the process, one side of the wafers was coated with a silicon nitride film [Fig. 1(a)], which serves as a mask during the anisotropic etching step. Next, the nitride film was patterned by conven-

![Side view](image1.png)

![Top view](image2.png)

FIG. 1. (a)–(d) Micromachining process steps. (e) The micromachined wafers can be stacked to form either fct (left side) or st (right side) type photonic crystal structures.
around 100 GHz. As shown in Fig. 1, the upper band edge, calculated to be located at 100 GHz,
determined the upper band edge, calculated to be located at 100 GHz.

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These planar defects also resulted in similar defect characteristics, however with higher transmission amplitudes. Figure 3(b) shows the transmission through a planar defect with separation width $L = 550 \mu m$ (solid line). The resonance frequency of the defect mode is at 90 GHz with a $Q$ factor of 25. As the separation of the cavity was increased to $L = 650 \mu m$, the resonance frequency of the defect mode shifted to 83 GHz (dotted line). These results indicate that the defect frequency can be tuned within the band gap by changing the width of the cavity.9

In order to understand the effect of doping concentration on defect characteristics, we compared our experimental results with the TMM simulations (Fig. 4). We used the same planar defect structure described above, with a separation width of 800 $\mu m$. The results of the simulations for a doping concentration of $10^{17}$ cm$^{-3}$, which corresponds to resistivity of 0.09 $\Omega \cdot cm$, is shown by triangles. As the doping concentration is increased to $10^{19}$ cm$^{-3}$ (resistivity of 0.006 $\Omega \cdot cm$), the simulation results showed a significant increase in the $Q$ factor and the transmission amplitude of the defect mode (Fig. 4, circles). Having lower resistivity, the measured transmission amplitude and $Q$ factor for our samples are higher (Fig. 4, solid line). The simulation results of a complete metallic structure, which is shown by squares, indicate that our results may still be improved to reach better defect characteristics using wafers with higher doping concentrations.

In conclusion, by using standard semiconductor micromachining techniques, we fabricated layer-by-layer quasimetallic photonic crystals. These crystals exhibited a metallicity gap with an upper band edge around 100 GHz. The rejection rate per layer obtained from fct type crystals (5.3 dB) was found to be superior to the rejection rates of similar dielectric photonic crystal structures (3.5–4 dB per layer at midgap frequencies). Cavities created by removing rods resulted in localized defect modes at certain resonant frequencies. We observed the tunability of this resonant frequency for planar type defects. We showed that the doping concentration of the wafers is an important factor in determining the defect characteristics, and proposed that photonic crystals fabricated with wafers having higher doping concentrations will have higher $Q$ factors and higher transmission amplitudes.

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