Multilayer silicon cavity mirrors for the far-infrared p-Ge laser

Todd W. Du Bosq, Andrey V. Muravjov, Robert E. Peale, and Christopher J. Fredricksen

Multilayer mirrors capable of >99.9% reflectivity in the far infrared (70−200 μm wavelengths) were constructed using thin silicon etalons separated by empty gaps. Calculations indicate that only three periods are required to produce 99.9% reflectivity because of the large difference between the index of refraction of silicon (3.384) and the vacuum (1). The mirror was assembled from high-purity silicon wafers, with resistivity over 4000 Ω cm to reduce free-carrier absorption. Wafers were double-side polished with faces parallel within 10 arc sec. The multilayer mirror was demonstrated as a cavity mirror for the far-infrared p-Ge laser. Dependence of reflectivity on design accuracy was considered.

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1. Introduction

In the visible and near IR, high-reflectivity mirrors are fabricated from multiple dielectric layers, typically formed from glassy materials such as SiO_2, TiO_2, ZrO_2, and ThF_4. However, such materials, and most other glasses and polymers, will not work in the far IR due to high absorption loss. Moreover, homogeneous metal films that are thick enough to provide high reflectivity have loss due to free-carrier absorption, which increases as the square of the wavelength.

This paper describes high-reflectivity mirrors formed from alternating layers of silicon separated by empty gaps. Some preliminary results were described in Refs. 1 and 2. Silicon has high far-IR transparency in the region of 10–1000 μm, except in relatively narrow bands where phonon absorption occurs. Intracavity laser absorption measurements, with up to 3 cm of silicon placed inside the cavity of a p-Ge laser at a 4 K operating temperature, show a negligible effect on the laser thresholds at ~100 μm wavelengths.[3] Since gain of the p-Ge laser is usually less than ~0.1 cm^{-1},[4] while the active crystal lengths are usually several centimeters, the absorption coefficient of the passive Si crystal at cryogenic temperatures is therefore much less than 0.1 cm^{-1}. At room temperature, Si phonon absorption amounts to approximately 0.01 cm^{-1} at wavelengths longer than 50 μm.[5] Free-carrier absorption losses for intrinsic Si at room temperature are also ~0.01 cm^{-1}.[5] Both types of absorption are strongly reduced when the Si crystal is cooled to liquid-helium temperatures.

Because of the large difference in the index of refraction between silicon (3.384) and vacuum, air, or helium (1), just three periods in the multilayer Bragg mirror produce 99.9% reflectivity. The principle was independently suggested and tested recently,[6] although accurate measurement of the achieved reflectivity was lacking. This paper presents results of a test in which a three-period Si-gap stack is used as a cavity mirror for the far IR p-Ge laser (1 W peak power, tuning range 70–200 μm, megahertz linewidth[4]). The low gain of this laser medium (0.01–0.1cm^{-1}) puts high demands on mirror reflectivity. By comparing observed laser thresholds with that obtained using a traditional mirror, we can determine a qualitative indication of achieved mirror reflectivity.

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2. Theoretical Considerations

Multilayer Bragg mirrors are assembled by stacking alternating thin films of different refractive index and appropriate thickness. The reflectivity R of the Bragg mirror is determined from the standard matrix

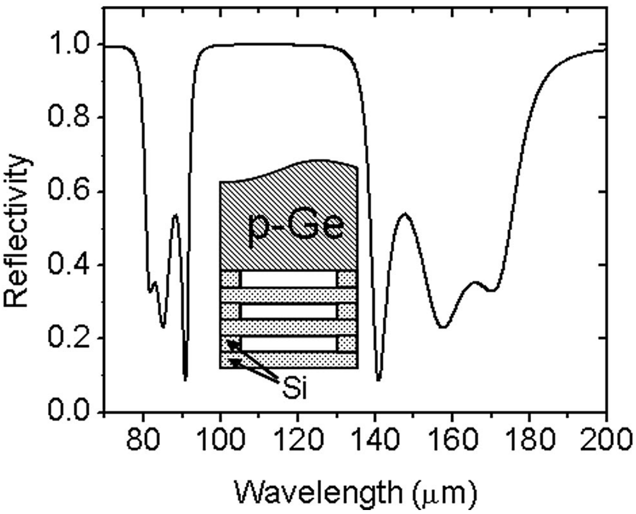

Fig. 1. Reflectivity (solid curve) of a three-period Bragg mirror in the emission wavelength range of the p-Ge laser with a Si layer thickness of 24.5 μm and a gap layer thickness of 27.6 μm. A maximum reflectivity of 99.93% is achieved. (Inset) Schematic drawing of the three-period Bragg mirror based on silicon and vacuum layers attached to the endface of an active p-Ge laser crystal.

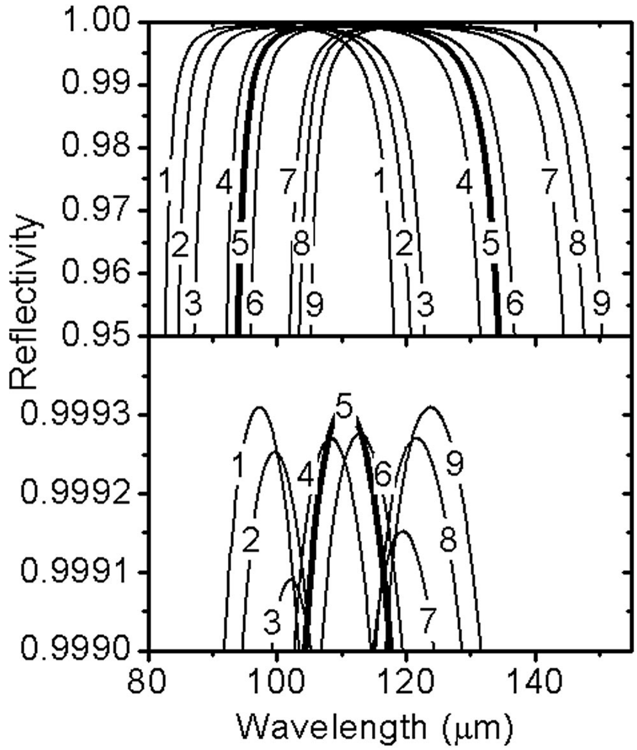

Fig. 2. Central high-reflectivity band for a three-period Bragg mirror in the emission wavelength range of the p-Ge laser. The (gap, Si) thicknesses in micrometers are as follows: 1, (24.6, 21.5); 2, (27.6, 21.5); 3, (30.6, 21.5); 4, (24.6, 24.5); 5, (27.6, 24.5); 6, (30.6, 24.5); 7, (24.6, 27.5); 8, (27.6, 27.5); 9, (30.6, 27.5).

formulation of the boundary conditions at the film interfaces found from Maxwell's equations.[7] A complex index of refraction is assumed. The real part of the refractive index of Si at 4 K and a 100 μm wavelength[8] is 3.384. The extinction coefficient of Si was taken to be 2.5×10^{-5} based on an upper bound estimate of 0.01 cm^{-1} for the absorption coefficient.[5] The refractive index of vacuum is unity.

A preliminary multilayer mirror was designed to serve as a cavity mirror for the p-Ge laser. The wavelength for peak R was chosen to be 110.5 μm, which corresponds to a region of relatively high transmission in the water-vapor spectrum.[9] This mirror is composed of just three periods of Si and vacuum gaps (Fig. 1). The thickness of each layer is a multiple of the quarter-wavelength of the light ($\lambda/4$) in the material. The Si layer thickness is 24.5 μm and the gap thickness is 27.6 μm. In the calculations, the incident medium was taken to be Ge (index of refraction of 3.925 at 4 K and a 100 μm wavelength[8]) and the medium behind the mirror is vacuum. Small 27.6 μm pieces of Si used as spacers determine the air layer thickness and ensure parallelism. The calculated reflectivity of the mirror is plotted versus wavelength in Fig. 1. over the operating range of the p-Ge laser. The maximum reflectivity for the three-period Bragg mirror is over 99.9%. Adding a fourth period increases the reflectivity to 99.99%.

The tolerance on absolute thickness specified by the manufacturer of the Si etalons used in the experiments (see below) is ±3 μm. Figure 2 presents the calculated central reflection peak for various combinations of the Si and gap thicknesses that have been changed by ±3 μm from the original design. The band of high reflectivity shifts by up to 20 μm as a result of these changes. Changing the thickness of the silicon has a larger effect than changing the gap thickness because the wavelength in the semiconductor is much smaller.

Figure 2 also presents a vertically expanded view of the central reflection peaks. Changing the gap and Si thickness simultaneously by 3 μm maintains the peak R at the level of 99.93%, but shifts the peak by 13 μm. The worst R value is still at the level of 99.91%. The peak R value changes by less than 0.023%. As noted, varying the Si thickness has a larger effect on wavelength position and R value than does varying the gap thickness.

Because extremely thin Si etalons are expensive, fragile, and difficult to manipulate, there is reason to consider the consequences using thicker stock. The calculated maximum reflectivity of a three-period Bragg mirror constructed with a gap thickness of 25 μm and the Si layer thickness between 10 and 100 μm thick is shown in Fig. 3 (bottom, solid curve). A consequence of increasing the etalon thickness is that the band with high reflectivity becomes narrower. Figure 3 (bottom, dashed curve) shows that the full width at half-maximum (FWHM) of the broadest high-reflectivity band, for the three-period Bragg mirror constructed with the 25 μm gap thickness, tends to decrease as the Si layer thickness is increased. Even for quite thick Si, the FWHM remains ~30 μm wide, which suggests that the corre-

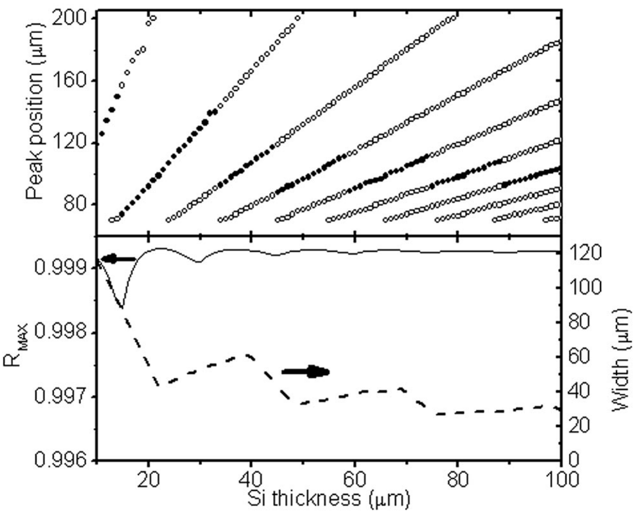

Fig. 3. Top: center wavelengths of bands with peak reflectivity above 95% for a fixed 25 μm gap and variable Si thickness in a three-layer Bragg mirror. Solid symbols indicate the band with highest reflectivity. Bottom: solid curve, maximum value of reflectivity; dashed curve, full width at half-maximum of the band with highest reflectivity.

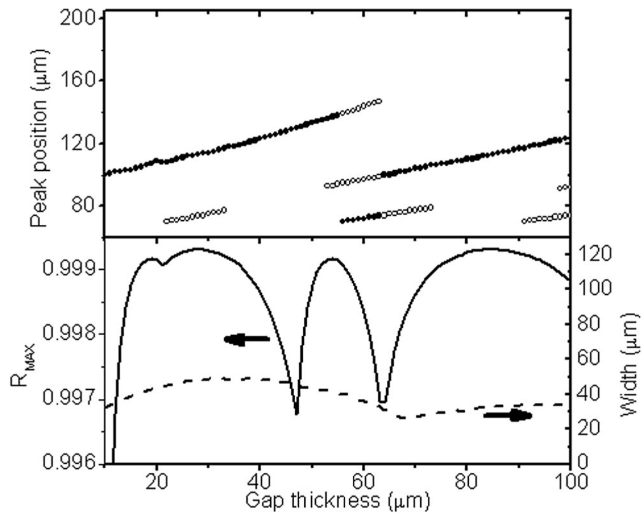

Fig. 4. Top, center wavelength of bands with peak reflectivity above 95% for fixed Si layer thickness and variable gap thickness. Solid symbols indicate the band with highest reflectivity. Bottom: solid curve, maximum value of reflectivity; dashed curve, full width at half-maximum of the band with highest reflectivity.

sponding mirror would still be useful in applications requiring broad wavelength tuning. The number of bands with reflectivity above 95% in the 70–200 μm wavelength range increases from 1 (see Fig. 1) to 7 as the thickness of each Si layer increases from 10 to 100 μm. The center wavelengths of the bands with the maximum R value above 95% are shown in Fig. 3 as the Si layer thickness is increased in steps of 1 μm. The band with the highest R value is represented by solid symbols. As the Si layer thickness is increased, the highest R value does not remain with the same band as it shifts to a longer wavelength, but rather jumps to the next band emerging from the low wavelength border into the considered range. The band with the highest R value tends to be the one with its center closest to the 100 μm wavelength, for which the 25 μm gap is one-quarter wavelength.

Calculations were also made for a three-period Bragg mirror constructed with a fixed 25 μm Si layer thickness and a gap thickness that varies over the range 10–100 μm. The calculated maximum reflectivity is plotted in Fig. 4 (bottom, solid curve) and its value exceeds 99.7% for most of the range of gap thickness considered. Figure 4 (bottom, dashed curve) shows that the FWHM of the broadest high-reflectivity band remains at least 25 μm, so that quite crude mirror structures remain valuable for applications that require broad wavelength tuning. The number of bands with reflectivity above 95% within the 70–200 μm wavelength range does not exceed three over the range of gap thickness considered. Their positions with reflectivity above 95% are plotted in Fig. 4 (top). The band with the highest R value is again represented by solid symbols. As the gap thickness is increased, the maximum R value jumps between the different bands, and it does not stay centered near a single wavelength. Note that high R values are absent for wavelengths beyond 150 μm with this type of construction.

It is more convenient and less expensive to construct Bragg mirrors of the type shown in Fig. 1 if both the Si etalon and the gap (formed from Si spacers) are the same thickness. In this case, all required pieces, both etalons and spacers, may be cut from the same wafer. The maximum reflectivity for such three-period Bragg mirrors is plotted versus layer thickness in Fig. 5 (bottom, solid curve). The reflectivity almost always exceeds 99.9%. A vertical line at 105 μm is drawn to indicate the thickness used in the experiments to be

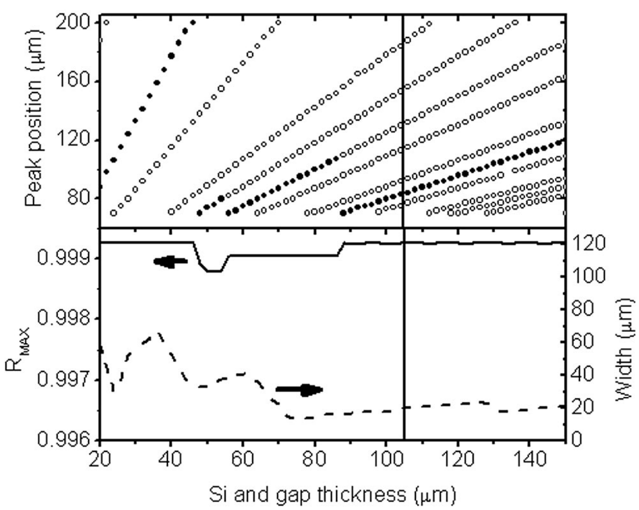

Fig. 5. Top, center wavelength of bands with reflectivity above 95% versus Si and gap thickness, which are the same. Solid symbols denote the band with the highest reflectivity. Bottom: solid curve, maximum value of reflectivity; dashed curve, full width at half-maximum for the band with highest reflectivity. The vertical line indicates the parameters for Bragg mirror B.

presented below. The FWHM of the broadest high-reflectivity band in the 70–200 μm wavelength range, plotted in Fig. 5 (bottom, dashed curve), tends to decrease as the layer thickness increases. However, the width always exceeds ~15 μm, showing that such mirrors remain useful for applications that require broad wavelength tuning. The number of bands with reflectivity above 95% increases as the layer thickness increases. The positions of bands with R values above 95% are plotted in Fig. 5 (top). The band with the largest R value is again represented by solid symbols. The preceding calculations indicate that, for use as a cavity mirror in a p-Ge laser whose gain bandwidth spans the 70–200 μm wavelength range, precise tolerances for Si or gap thickness are inessential.

3. Experiment

High-purity Si wafers were obtained from Valley Design. High resistivity, specified to exceed 4000 Ω cm, was chosen to minimize free-carrier absorption. Wafers were double-side polished and parallel within 10 arc sec, which is sufficient to prevent beam walk-off from the laser cavity during the 1 μs laser pulse. The specified Si thickness was 24.5 ± 3 μm and the gap thickness was 27.6 ± 3 μm for Bragg mirror A. The parallel gaps are produced using small 27.6 μm pieces of silicon as spacers. Wafer thicknesses were measured using a precision dial indicator (Starrett F2730-0) to be 25 ± 1 μm for the Si layer and 29 ± 1 μm for the gap spacers. These measurements indicate that curve 5 of Fig. 3 corresponds most closely to our actual experimental situation. Bragg mirror B is constructed using 105 ± 1 μm Si etalons for both the Si layers and the gap spacers, which corresponds to the configuration indicated by the vertical line in Fig. 5.

The multilayer mirrors are tested as cavity back mirrors for the p-Ge laser. The silicon pieces are stacked layer by layer onto the p-Ge crystal endface. After the six alternating layers are constructed, a brass washer is placed on top of Bragg mirror A with a rubber string attaching the whole structure in place on the crystal, as pictured in Ref. 2. Bragg mirror B was stacked onto the p-Ge laser and held in place using a bronze spring. A $SrTiO_3$ mirror, smaller than the crystal endface to allow radiation output, is attached to the other endface of the crystal.[2] The active Ga-doped Ge ($N_A \sim 7 \times 10^{13}$ cm^{-3}) crystal has dimensions of 35.20 mm × 4.75 mm × 6.75 mm for Bragg mirror A and 45.45 mm × 6.0 mm × 2.5 mm for Bragg mirror B. The crystal ends were polished flat and parallel within 30 arc sec. The electric field was generated in the crystal by applying voltage with a thyratron pulser to the ohmic contacts. The magnetic field was supplied by a superconducting solenoid. A liquid-helium-cooled Ge:Ga photoconductor inside the cryostat detects the radiation.

Lasing is observed using both mirrors A and B. The laser operation zones, i.e., the applied electric and magnetic fields for which the laser operates, were recorded for the different end mirrors. Figure 6 presents the laser operation zones by use of Bragg mirrors A and B in the space of applied **E** and **B** fields compared with that of a $SrTiO_3$ end mirror. The electric and magnetic field thresholds are higher for B than for A. Both mirrors have higher thresholds than found with a $SrTiO_3$ back mirror.

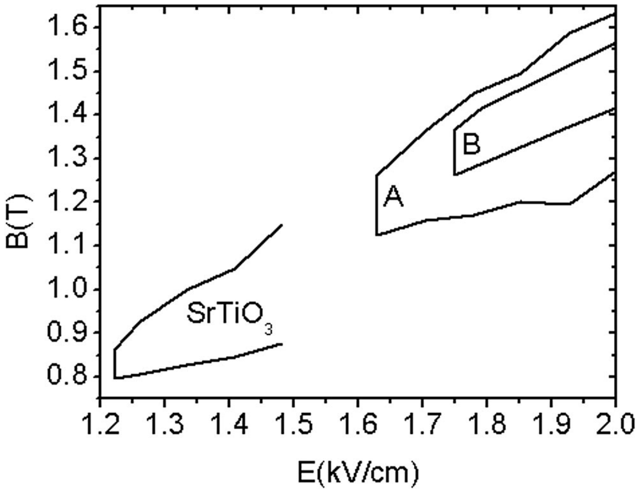

Fig. 6. Comparison of the laser generation zones for the p-Ge laser by use of two different Bragg mirrors or $SrTiO_3$ mirror. Bragg mirror A is constructed with a 29 μm gap layer thickness and 25 μm Si layer thickness. Bragg mirror B is constructed with a 105 μm Si and gap layer thickness.

4. Discussion

Figure 6 is an experimental demonstration that a Si and gap multilayer Bragg mirror has sufficient reflection for use with the low-gain, far-IR p-Ge laser. The mirror reflectivity R must satisfy the condition

$$R \geq \exp(-2\alpha L_{\mathrm{Ge}}), \tag{1}$$

where α is the gain and L_{Ge} is the length of the Ge laser cavity. Using 0.01 cm^{-1} as the value for the gain of a p-Ge laser and 3.52 cm for the length of the laser crystal, the minimum reflectivity for a laser mirror is $R_{\mathrm{min}} \sim 93\%$. Output coupling losses require the reflectivity to be better than 93%. $SrTiO_3$ has a reflectivity of ~99% at 20 K in this wavelength region,[10] although this R value should increase as the mirror temperature decreases to 4 K. The higher thresholds for the Bragg mirrors therefore suggest that their reflectivity is somewhat lower than 99%. Hence, while these experiments bracket the reflectivity of the Bragg mirror in the range of 93–99%, they fail to definitely confirm the predicted 99.9% value. Bragg mirror B has a higher threshold than mirror A, in agreement with calculations (Figs. 2 and 5) that suggest narrower bands of high reflectivity for the thicker layered structure. Nevertheless, the laser operation with Bragg mirror B shows that a highly reflective mirror can be constructed using layers of equal thickness that are much larger than a quarter wavelength.

As an explanation for the high thresholds with the Bragg mirrors despite their high calculated reflectivity, we note that the brass washer and Si spacers for the stack overlap portions of the active-crystal endface that might support laser modes. Such regions of the mirror lack the calculated high reflectivity. A more monolithic construction could be made by wet chemical etching to produce the gaps,[11] eliminating the need for the small Si spacers. Nevertheless, the preliminary experiments described here demonstrate that mirrors of sufficient reflectivity for use in the cavity of the low-gain p-Ge laser can be made with just a few layers of Si separated by empty gaps. Furthermore, high design precision does not appear to be critical.

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