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Wavelength selection for the far-infrared p-Ge laser using etched silicon lamellar gratings

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Abstract

A lamellar mirror made from Si wafer by anisotropic chemical etching and coated with gold has been demonstrated as an intracavity wavelength selector for the far-infrared p-Ge laser. The etching process produces rectangular grooves with precisely predetermined depth and 100 nm surface smoothness. This lamellar-grating structure defines the resonant laser wavelength within the broad tuning range of the p-Ge laser. Single wavelength laser operation with this mirror has been demonstrated on the third-order resonance with an active cavity finesse of at least 0.09.

Keywords: Terahertz; Germanium; Laser

1. Introduction

With its high peak power (1 W) and broad tuning range (1.5–4.2 THz, 70–200 μm), a p-Ge laser [1] with practical means of selecting a narrow emission line would have value in chemical spectroscopy and sensing. Recent advances in quantum cascade laser (QCL) technology provides laser emission at any wavelength within the same THz range spanned by the p-Ge laser [2,3]. However, each new wavelength requires development and molecular beam epitaxy of a new QCL structure. This paper presents a relatively simple method of selecting wavelength using the p-Ge laser with selective lamellar mirror.

Because of the anomalously wide p-Ge laser gain bandwidth, the spectrum of the laser emission is approximately 20 cm^{-1} wide unless special selectors are used. For the usual cavity lengths (>10 cm) determined by optical length of the active crystal, this 20 cm^{-1} band contains several hundred longitudinal modes. Intra-cavity wavelength selection based on lamellar gratings [4] have been reported [5,6], where the active cavity finesse can exceed unity, which results in single longitudinal mode emission [7]. Piezo-control of the selector has allowed fine tuning between nearby longitudinal modes [8]. A variable-length cavity was demonstrated, which in principle allows continuous tuning without mode hops [9].

Selector design has been constrained by the cryogenic environment, high operating voltages, and high index of refraction of germanium. In the tunable lamellar-gratings used to date, a silicon spacer has supported aluminum stripes and isolated the high-voltage laser-excitation pulse from the metal tuner parts [5–8]. A disadvantage of this design is the appearance of unwanted wavelength-selective resonances introduced by the silicon spacer itself [8,10]. The pattern of evaporated stripes is difficult to experimentally optimize for highest selector Q. Also, a piston [5–8] that assures parallel changes in the air gap of the tuner tends to stick at the cryogenic p-Ge laser operating temperatures. When this piston is piezo-controlled, only small displacements can be achieved even with high control voltages, resulting in a limited tuning range [8]. This problem is compounded by the four-fold reduction of piezo action upon cooling to 4 K.

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Clearly, new selector concepts are required for the p-Ge laser. A promising approach toward developing new selector designs is silicon process technology. Recently, we demonstrated a fixed wavelength selector based on a simple silicon intracavity etalon [11,12]. In this paper, we explore a new type of fixed wavelength selector made by etching a lamellar structure into silicon, which is then coated with gold and used as a back mirror.

2. Experimental details

Silicon micromachining takes advantage of anisotropic alkaline-type etchants. Tetramethyl ammonium hydroxide (TMAH) is an effective wet etchant, which produces smooth mirror-like etched surfaces. The etch rates vary from 0.5 to 1.4 μm/min and 0.1–0.2 μm/min at 80°C for [1 0 0] and [1 1 0] silicon, respectively. Orientation-dependent etching for [1 1 0]-oriented silicon through a patterned SiO_2 mask creates nearly straight-walled grooves with [1 1 1]-side planes. Deep vertical cavities up to 150 μm can be fabricated with a depth control of 1 μm.

Mask patterns produced using AutoCAD were transferred as chrome onto a 63.5 mm × 63.5 mm × 1.52 mm soda lime glass plate with a critical dimension tolerance ±10 μm by Adtek Photomask. Silicon wafers ([1 1 0]-oriented, 50 mm diameter, single side polished) were oxidized to produce an etch mask layer. Negative photoresist was spun on and then baked at 150°C for 1 min. The mask pattern was applied using a mask aligner and 10 s exposure. The wafer was then baked at 100°C for 1 min and developed, after which the wafer was baked at 150°C for 3 min. The oxide in the masked areas was stripped using buffered oxide etch (BOE). Acetone and methanol removed the remaining photoresist and the exposed silicon was etched for 2 h with 20 parts TMAH, 70 parts deionized water, and 10 parts isopropyl alcohol at 90°C. Isopropyl alcohol was added at regular intervals to insure smooth surfaces. The wafer was removed from the etching bath and immersed in BOE to strip the remaining oxide.

A table-top sputtering system evacuated by a mechanical pump without trap deposited 150 nm of AuPd onto the etched mirror. The samples were removed and transferred to an evaporator for a 450 nm coating of Au to give it high far-IR reflectivity. The depth of the trenches was determined with an optical microscope. Taking the difference between the focus of the top of the selector and the bottom of the trench, the depth was determined with an uncertainty of 5 μm. Width of features in the plane was determined using a micrometer controlled translation stage and the optical microscope, which was equipped with a cross-hair eyepiece.

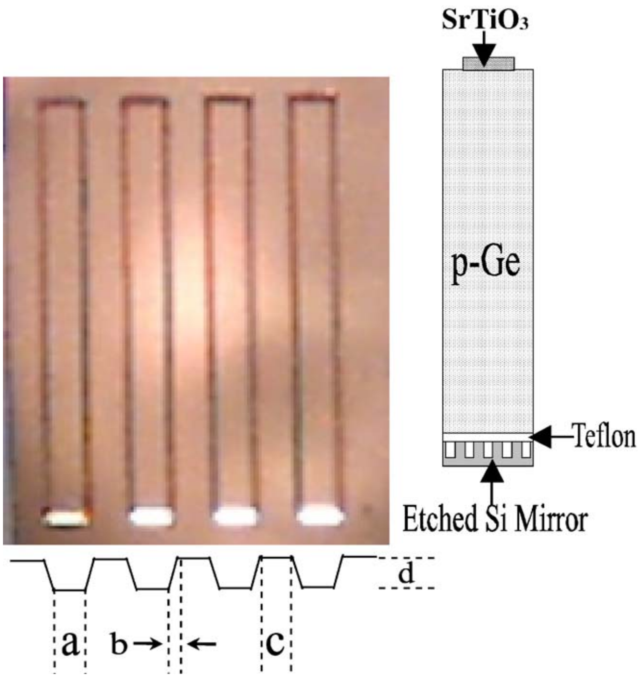

Fig. 1. (right) Schematic of the p-Ge laser with the silicon etched mirror used for wavelength selection. (left) Photograph of silicon etched mirror B after AuPd sputtering and Au evaporation. (bottom) Schematic definition of mirror geometrical parameters.

An atomic force microscope (AFM; Veeco Metrology Nanoscope IIIA) characterized roughness and surface features of one finished mirror. To image the bottom surface of the trenches, the front corners of the cantilever chip (TAP300, Nanodevices) were mechanically removed by chipping the silicon with a scalpel. Roughness was determined at several locations in the trenches and on the top surface. The thickness of the metal coating was confirmed by measuring a pinhole that exposed the silicon surface.

The laser active crystals were made from the p-type germanium purchased from Tydex (St. Petersburg, Russia). The crystals were cut into rectangular rods of dimensions 45.75 mm × 5.90 mm × 2.65 mm (crystal 1) and 44.95 mm × 5.80 mm × 2.85 mm (crystal 2) with crystallographic orientations of its three axis as [1 1 0], [1 −1 0] and [1 0 0], respectively. The length of the crystals defined a longitudinal mode separation of $\sim 0.028\ \mathrm{cm}^{-1}$ for each, using an index of refraction of Ge at 4 K and 100 μm wavelength of 3.925 [13]. End faces were hand polished flat and parallel within 30 arcsec by a technique described in Ref. [14]. Indium ohmic contacts were applied to opposite [1 −1 0] lateral faces with an ultrasonic soldering iron [14]. Electric field pulses with 1–2 μs duration were applied to an active crystal in the [1 −1 0] direction with a thyratron pulser at repetition rates of 1–8 Hz. A magnetic field was applied along [1 1 0] active crystal axis using a home-built superconducting solenoid. The laser cavity construction, shown in Fig. 1, consists of the lamellar selective mirror, 20 μm Teflon film, the active crystal, and the $SrTiO_3$ output mirror, which is smaller than the active crystal end face to allow output coupling around its edges. The output laser radiation was detected by a 4 K Ge:Ga detector or a 4 K Si bolometer. Spectra of the output laser radiation were