

# Fabrication and performance of thin amorphous Si subwavelength transmission grating for controlling vertical cavity surface emitting laser polarization

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Amorphous Si subwavelength transmission gratings (SWTGs) with a thickness of 240 nm and a period ranging from 50 to 900 nm were fabricated on a fused silica substrate using electron beam lithography, lift-off, and reactive ion etching. At certain grating periods, the SWTGs exhibit polarization dependent reflectance and transmittance due to the polarization dependent coupling of the eigenmodes inside the grating. By putting the SWTG in front of the output window of a vertical cavity surface emitting laser (VCSEL), a polarization dependent optical feedback can be achieved. Using this feedback, we demonstrated the locking, switching, and enhancement of the VCSEL's polarization. A polarization ratio as high as 200:1 was achieved. © 1996 American Vacuum Society.

## I. INTRODUCTION

Vertical cavity surface emitting lasers (VCSELs) have a potentially wide range of applications as light sources due to their low drive current, high efficiency, single mode operation, and high integration capability. In many applications, such as magneto-optical recording, polarization dependent sensors, high efficiency optical interconnection, and uniformly polarized VCSEL arrays, highly polarized light sources are required. However, the output of a conventional VCSEL has two linearly polarized orthogonal modes along the  $\langle 011 \rangle$  and the  $\langle 0\bar{1}1 \rangle$  crystal directions.<sup>1</sup> Under normal operation, both modes exist in the output with one mode strong and the other weak. The typical polarization ratio is around 20:1. Furthermore, the orientation of the dominant mode is random and in some cases, as the drive current increases, the dominant mode can switch by itself to the weak mode. Efforts have been made to control the VCSEL's polarization by using an anisotropic transverse cavity geometry,<sup>2,3</sup> stress from an elliptical window,<sup>4</sup> asymmetric active layers,<sup>5</sup> or metal gratings as the bottom reflector.<sup>6</sup> However, these methods all involve direct manipulation of the VCSEL's internal cavity structure. In many applications, it is more desirable to obtain polarization control without significantly changing the internal cavity structure.

In this article, we demonstrated polarization control of VCSELs through a polarization dependent optical feedback that uses thin amorphous silicon subwavelength transmission gratings (SWTGs). We have achieved not only polarization mode locking, but also mode switching and mode enhancement.

## II. PRINCIPLE OF POLARIZATION CONTROL

As suggested in Ref. 7, the principle of controlling a VCSEL's polarization is based on the observation that

SWTGs have a polarization dependent reflectivity. When a SWTG is put in front of the output window of a VCSEL, one polarization mode is reflected back into the laser cavity more favorably than the other mode, forcing the lasing polarization to be locked in the favored reflected mode. Therefore, a SWTG can either enhance the dominant polarization or switch the polarization. In polarization locking, the SWTG is arranged to reflect back the dominant mode in a VCSEL's output more favorably into the cavity, making the mode even stronger than before and the weak mode significantly reduced. In polarization switching, the SWTG is arranged to reflect back the weak mode more favorably than the dominant mode, making it a dominant mode while switching the original dominant mode into a weak mode.

## III. FABRICATION OF SWTGs

Amorphous silicon subwavelength transmission gratings on a silica substrate were designed especially for the VCSELs with an output wavelength of 850 nm. Amorphous silicon was used because it has a high refractive index that is necessary to bring up more than one eigenmode inside the grating to create polarization effects.<sup>7</sup> The amorphous silicon film, 240 nm in thickness, is nearly transparent for 850 nm light because of a large effective band gap and a small thickness. In fabrication, a 240 nm thick amorphous silicon layer was first evaporated on a 0.5 mm thick silica substrate. Poly-methyl methacrylate, of 950 K molecular weight and 70 nm thickness, was spun on the top. Electron-beam lithography was used to pattern the gratings with a period ranging from 50 to 900 nm and a duty cycle (i.e., the ratio of linewidth to period) of  $\sim 0.45$ . After development, a layer of Cr was evaporated and lifted off. This Cr pattern served as the mask in the following reactive ion etching (RIE) of amorphous silicon. In the RIE of amorphous silicon,  $\text{Cl}_2$ ,  $\text{SiCl}_4$ , and  $\text{Ar}_2$  with flow rates of 40, 16, and 20 sccm, respectively, a pressure of 25 mTorr, and a power of 150 W were used. The Cr mask was removed after the RIE. A scanning electron mi-

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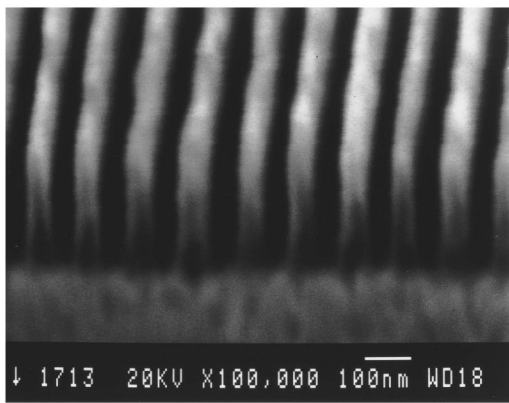


FIG. 1. SEM micrograph of the cross section of the amorphous silicon SWTG with 100 nm period and a thickness of 240 nm.

crograph (SEM) of the cross section of a 100 nm period grating is shown in Fig. 1. The thickness is 240 nm and the duty cycle is about 0.45, as designed. It has a very high aspect ratio and the profile is nearly rectangular.

#### IV. EXPERIMENTAL RESULTS

We measured the reflectance of the SWTGs with different periods. The light source is a commercially available VCSEL of 20  $\mu\text{m}$  diameter, lasing at a wavelength of 850 nm. Figure 2 shows the measured reflectance of the amorphous silicon SWTGs as a function of the grating period for the TE mode (polarization direction parallel to grating fingers) and TM mode (polarization direction perpendicular to grating fingers). Obviously, the SWTGs have different reflectances for TE and TM modes, making it a polarization dependent partial reflector. The polarization dependent reflectance varies with the period of the gratings. Theoretical calculation showed that the polarization effects also depend on the duty cycle, thickness, and dielectric constant of the gratings. Figure 2 shows that the 100 nm period grating has a suitable polarization dependent reflectance for VCSEL polarization

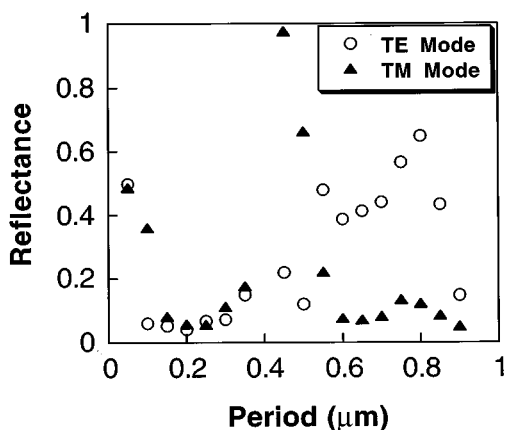


FIG. 2. Measured reflectance of the SWTGs vs the grating period for a wavelength of 850 nm.

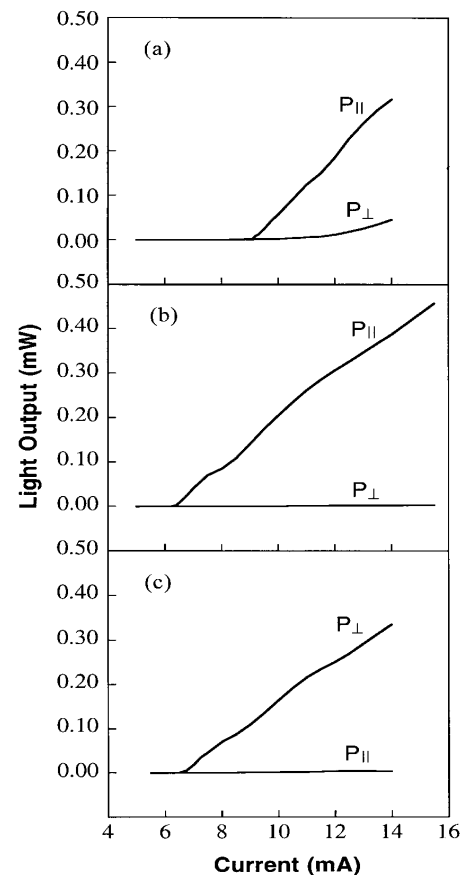


FIG. 3. VCSEL's output vs the drive current, (a) without feedback; (b) with feedback grating fingers perpendicular to  $P_{\parallel}$ ; and (c) with feedback grating fingers parallel to  $P_{\parallel}$ . SWTG has a period of 100 nm.

control. Namely, this grating has a low TE mode reflectance (7%) and a reasonable TM mode reflectance (35%). This 100 nm period grating might have a different duty cycle and uniformity than the one shown in Fig. 1.

Figure 3(a) shows the output versus the drive current for the VCSEL without feedback. The dominant polarization mode for the laser is denoted as  $P_{\parallel}$  and the weak mode as  $P_{\perp}$ , which is perpendicular to  $P_{\parallel}$ . The intensity of the weak mode is  $\sim 5\%$  of the dominant mode.

When we put the 100 nm period grating in front of the VCSEL's output window and align the grating fingers perpendicular the  $P_{\parallel}$  direction, the dominant mode  $P_{\parallel}$  is reflected back more favorably than the  $P_{\perp}$  mode. As pointed out before, once the favorably reflected back light is injected into the laser cavity, it would force the polarization of subsequent stimulated emission in the same direction and lock the polarization. In this case, the originally dominant mode is enhanced and the weak mode suppressed, as shown in Fig. 3(b). This polarization locking effect is more clearly illustrated in the polarization ratio versus the drive current curve in Fig. 4. When there is no SWTG, the maximum polarization ratio of the VCSEL's output is about 20:1. However, in the polarization locking case, the polarization ratio is significantly increased. A maximum of 200:1 is reached. In higher drive current, the polarization ratio decreases. It is believed

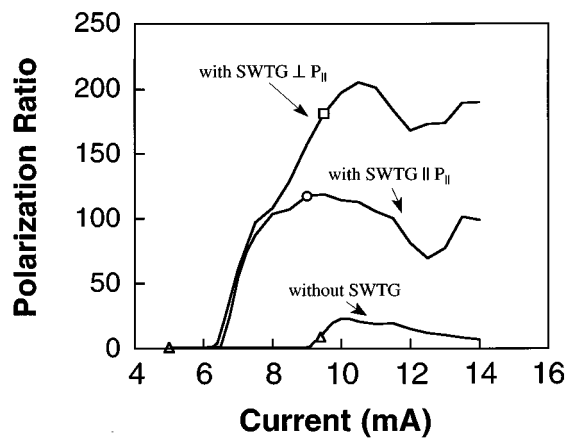


FIG. 4. The polarization ratio vs the drive current for the cases: (a) a conventional VCSEL  $\Delta$ , (b) polarization locking  $\square$ , and (c) polarization switching  $\circ$ .

that higher order modes appear in this high current regime, reducing the polarization ratio.

Figure 3(c) shows the output power of the VCSEL versus drive current when the grating is turned  $90^\circ$  so that the grating fingers are aligned parallel the  $P_{||}$  direction. The weak mode  $P_{\perp}$  is now more favorably reflected. Therefore, the  $P_{\perp}$  mode becomes the dominant mode, whereas the original strong  $P_{||}$  mode is switched to the weak mode. As shown in Fig. 4, the maximum polarization ratio changes from 1:20 (no SWTG) to 150:1 (with SWTG). This mode switching clearly shows that the favorably reflected mode has forced the laser to operate in the injected mode.

Polarization locking, switching, and polarization ratio enhancement were also observed for gratings with other periods. In fact, a polarization ratio of more than 300:1 was obtained using a 450 nm period grating that has a nearly 90% reflectance for the TM mode. However, this high reflectance also prevented the enhanced light from passing through the SWTG, leading to a low extra-cavity output for that mode. For periods greater than 500 nm, diffraction effects start to become significant, reducing the effectiveness of the SWTG in polarizing the VCSEL.

## V. SUMMARY

We fabricated amorphous silicon subwavelength transmission gratings that have polarization dependent reflectivity and transmittivity. Using these gratings as a polarization dependent partial reflector, we demonstrated controlling the VCSEL's polarization output by optical feedback. Polarization mode locking, mode switching, and polarization ratio enhancement (as high as 200:1) have been achieved. Due to the ultrathin feature, the SWTGs can be monolithically integrated on to the VCSEL array for unique application.

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