Design and Fabrication of Zinc Oxide Thin-Film Ridge Waveguides on Silicon Substrate With Ultraviolet Amplified Spontaneous Emission

S. F. Yu, *Senior Member, IEEE*, Clement Yuen, S. P. Lau, and W. J. Fan

***Abstract*—Zinc oxide (ZnO) thin-film ridge waveguides have been designed and fabricated on n-type (100) silicon substrate. A filtered cathodic vacuum arc technique is used to deposit high-crystal-quality ZnO thin films on lattice-mismatched silicon substrates at 230 °C. A ridge waveguide of width $\sim$ 2 μm and height $\sim$ 0.1 μm is defined on the ZnO thin film by plasma etching. Room-temperature amplified spontaneous emission is observed with peak wavelength at $\sim$385 nm under 355-nm optical excitation. It is found that the net optical gain of the ZnO thin-film ridge waveguides can be as large as 120 cm^{-1} at a pump intensity of $\sim$ 1.9 MW/cm^2.**

***Index Terms*—Amplified spontaneous emission, filtered cathodic vacuum arc technique, optical waveguide, ultraviolet emission, zinc oxide.**

I. Introduction

ULTRAVIOLET (UV) light-emitting devices and lasers find enormous applications in commercial products (e.g., ultrahigh-density storage in CDs and DVDs), scientific research (e.g., low-cost activated biological or chemical sensors) as well as military applications (e.g., portable on-site detector for natural or human caused epidemics). Zinc oxide (ZnO) has a bandgap of 3.37 eV and a large exciton binding energy of 60 meV at room temperature. Hence, it is one of the most promising candidates to achieve effective room-temperature UV emission. Recently, progress in the fabrication of ZnO thin films by plasma-assisted molecular-beam epitaxy (P-MBE) [1], [2], pulsed laser deposition (PLD) [3], and metalorganic chemical vapor deposition (MOCVD) [4], [5] has led to the growth of high-quality ZnO thin films. In addition, room-temperature stimulated emission and lasing from the ZnO thin films under optical pumping have been demonstrated [6], [7]. However, the growth of high-quality ZnO thin films requires the use of (0001) sapphire as substrate, which may limit the application of ZnO thin films for the development of UV optoelectronics [8], [9]. This is because sapphire substrate is an expensive material and difficult to process (i.e., difficult to cleave). Therefore, developing a cost-effective technique to deposit ZnO thin films on low-cost substrates like silicon is particularly important, where the quality of films is comparable to that obtained from P-MBE, PLD, or MOCVD techniques.

In this paper, the design, fabrication, and characterization of ZnO thin-film ridge waveguides are reported. The fabrication of high-quality ZnO thin films on silicon substrates is demonstrated by using the filtered cathodic vacuum arc (FCVA) technique at relatively a low substrate temperature of $\sim 230\,^\circ$C [10]. Furthermore, a ridge structure is formed on the ZnO thin film by plasma etching. The main advantages of using the FCVA technique to fabricate ridge waveguides are: 1) the possibility of depositing high-crystal-quality ZnO thin films on lattice-mismatch silicon substrates; 2) low-temperature process; and 3) the ability to be scalable to large-area substrate (up to 8$''$ in diameter in our system). It is demonstrated that the ZnO thin-film ridge waveguides emit high-intensity UV amplified spontaneous emission (ASE) under optical excitation and the maximum net optical gain can be as high as 120 cm^{-1}. Hence, this indicates that the quality of our ZnO thin film on silicon is compatible to P-MBE, PLD, or MOCVD techniques grown on sapphire. Furthermore, the capability to grow ZnO thin films on silicon substrates allows the mass production of UV optoelectronics as well as the integration of II–VI materials with silicon-based electronics.

II. Design of ZnO Ridge Waveguides on Silicon

In the fabrication of ZnO thin-film waveguides on sapphire, only a layer of ZnO thin film with thickness d_a is required to be deposited on the substrate. This is because the refractive index of the ZnO thin film ($\sim$2.1) is larger than that of the sapphire substrate ($\sim$1.79) so that the transverse confinement of light can be realized by total internal reflection inside the ZnO thin film. In addition, the thickness of ZnO thin film d_a should be greater than $\lambda_R/4n_{\text{eff}}$, where n_{eff} is the effective refractive index and λ_R is the operating wavelength [11]. However, the direct deposition of ZnO thin film on silicon substrate cannot sustain total internal reflection inside the ZnO thin film. This is due to the fact that the refractive index of silicon ($\sim$3.45) is greater than that of ZnO thin film. In order to realize transverse optical confinement inside the ZnO thin films using silicon as the substrate, a buffer layer with a refractive index lower than that of ZnO should be inserted between the ZnO thin film and silicon substrate. It fact, silicon dioxide $(\mathrm{SiO_2})$ is the most appropriate choice as the buffer layer because $\mathrm{SiO_2}$: 1) has a refractive index ($\sim$1.45) smaller than that of ZnO thin film; 2) has very

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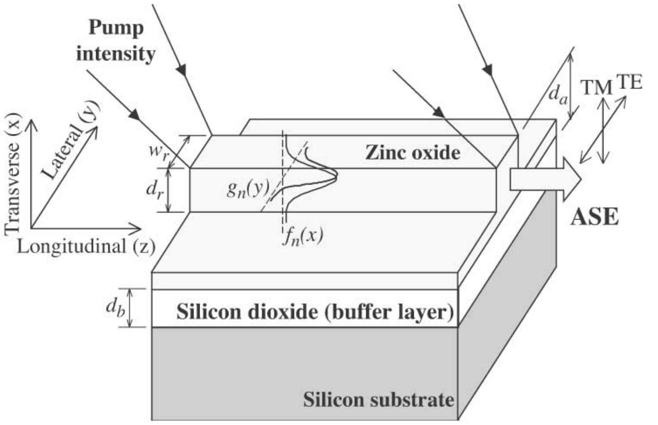


Fig. 1. Schematic of the ZnO thin-film ridge waveguide using silicon as the substrate. $f_n(x)$ and $g_n(y)$ are the transverse and lateral field profiles, respectively.

small absorption loss due to its wide energy gap ~9 eV, and 3) can be easily obtained on silicon substrate by thermal oxidation [12]. Furthermore, a ZnO ridge structure, which confines optical power along the lateral direction of the waveguide, can be easily formed by plasma etching. Fig. 1 shows the proposed ZnO ridge waveguide on silicon substrate.

In the design of a ZnO ridge waveguide, it is required to select the necessary thickness of ZnO thin film d_a, thickness of SiO$_2$ d_b, height of the ridge d_r, and the width of the ridge w_r so that: 1) the coupling coefficient Γ_c or the overlapping area between the signal and pump intensities inside the ridge waveguide can be maximized and 2) the absorption loss inside the silicon substrate α_{eq} can be minimized. It can be shown that the expression of Γ_c is given by

$$\begin{aligned}\Gamma_c &\cong \Gamma_{\mathrm{cx}} \times \Gamma_{\mathrm{cy}} \\ &\equiv \int\limits_{d_a} |f_s(x)|^2\,dx \int\limits_{d_a} |f_s(x) f_p(x)|\,dx \\ &\quad\times \int\limits_{w_r} |g_s(y)|^2\,dy \int\limits_{w_r} |g_s(y) g_p(y)|\,dy \qquad (1)\end{aligned}$$

where f_n (g_n) is the normalized field profile along the transverse (lateral) direction, and $n = s$ (p) represents the signal (pump) field. Γ_{cx} and Γ_{cy} are defined as the transverse and lateral coupling coefficients, respectively. Furthermore, α_{eq} can be written as

$$\alpha_{\mathrm{eq}} = \alpha_{Si} \int\limits_{\mathrm{substrate}} |f_s(x)|^2\,dx \qquad (2)$$

where α_{Si} $(\sim 10^4\ \mathrm{cm}^{-1})$ is the absorption loss in silicon [12]. In order for the proposed ridge waveguide to yield a similar optical performance as that of the ZnO thin films fabricated on sapphire substrate, it is required to set the constraints: 1) $\Gamma_{\mathrm{cx}} \times \Gamma_{\mathrm{cy}} > 0.9$ and 2) $\alpha_{\mathrm{ed}} < 1.0\ \mathrm{cm}^{-1}$ so that the most appropriate values of d_a, d_b, d_r, and, w_r can be determined.

Fig. 2 plots the variation of Γ_{cx} and α_{eq} versus d_b with d_a varying from 0.14 to 0.27 μm. In the analysis, only the fundamental TE mode is considered in the calculation of $f_n(x)$ because it has the lowest threshold gain [11]. In addition, the wavelength of the signal and pump are set to 385 and 355 nm, respectively. It is noted that the cutoff of the first-order transverse mode occurs if $d_a <\sim 49$ nm. It is observed that, for $d_a \geq 0.16$ μm, the values of Γ_{cx} (α_{eq}) are greater (less) than 0.9 (1.0 cm^{-1}) for $d_b > 0.40$ μm. These imply that the constraints $\Gamma_{\mathrm{cx}} > 0.91$ and $\alpha_{\mathrm{eq}} < 1.0\ \mathrm{cm}^{-1}$ can be easily obtained for $d_a \geq 0.16$ μm provided that $d_b > 0.40$ μm. Hence, $d_b =\sim 0.42$ μm is selected because our fabrication facilities can only guarantee to produce SiO$_2$ thin films up to this thickness with satisfactory surface roughness for waveguide applications. In this case, the value of $d_a \sim 0.16$ μm must be selected in order to maintain $\alpha_{\mathrm{eq}} < 1\ \mathrm{cm}^{-1}$ and to minimize the number of transverse modes. For $d_a \sim 0.16$ μm, the maximum number of transverse modes that can be supported inside the ZnO thin films is <4. Furthermore, the corresponding value of Γ_{cx} is ~0.91 so that the required value of Γ_{cy} to achieve $\Gamma_c > 0.9$ is >0.989.

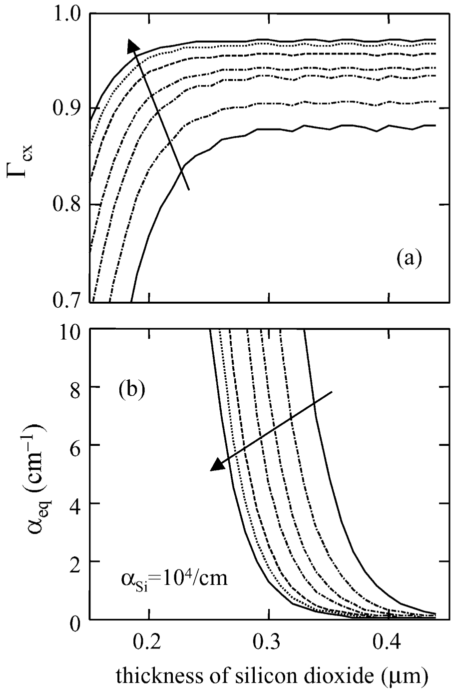


Fig. 2. (a) Transverse coupling coefficient Γ_{cx} versus thickness of the SiO$_2$ buffer layer d_b for different thicknesses of ZnO thin film d_a (from bottom to top $d_a = 0.18$, 0.20, 0.30, 0.25, and 0.27 μm). (b) Absorption loss α_{eq} versus thickness of the SiO$_2$ buffer layer d_b for different thicknesses of ZnO thin film d_a (from top to bottom $d_a = 0.18$, 0.20, 0.30, 0.25, and 0.27 μm).

Fig. 3 shows the variation of Γ_{cy} versus w_r with d_r varying from 0.03 to 0.15 μm. The thicknesses of d_a and d_b are selected to be 0.16 and 0.42 μm, respectively, in the calculation. Again, only the fundamental TE mode is considered in the calculation of $g_n(y)$. It is observed that, if $w_r > 2.0$ μm, the requirement of $\Gamma_{\mathrm{cy}} > 0.989$ will satisfy if $d_r \geq 0.1$ μm. The desired values of w_r and d_r are selected to be ~2 and 0.1 μm, respectively. This is because the number of lateral modes to be supported by this ridge structure is minimum. For this selection of w_r and d_r, the maximum number of lateral modes that can be sustained inside the ridge structure is ≤5. TM modes can also be investigated in the same manner, and the results are quite similar to those given in Figs. 2 and 3 except that the values of Γ_{cx} and Γ_{cy} are ~6%–10% lower than that of the TE modes. This implies that

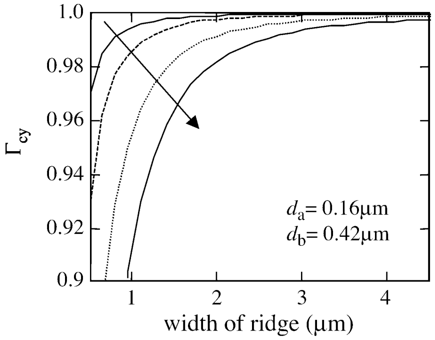


Fig. 3. Lateral coupling coefficient Γ_{cy} versus width of the ridge structure w_r for different depths d_r of the ridge structure (from top to bottom $d_r = 0.15$, 0.1, 0.05, and 0.03 μm).

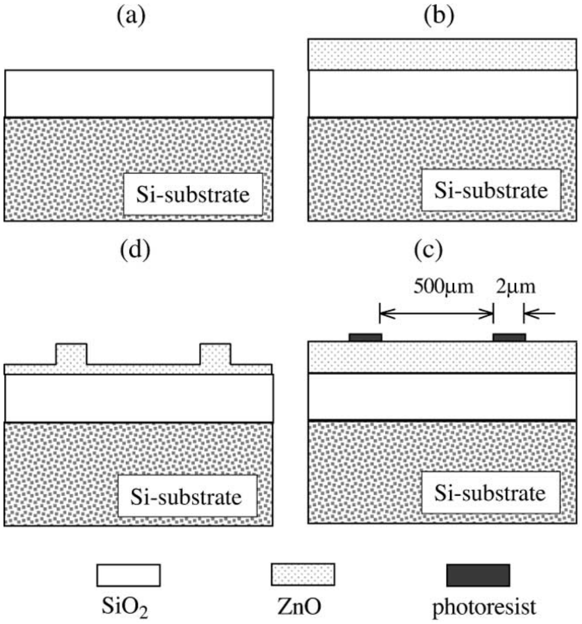


Fig. 4. Fabrication procedures of the proposed ZnO ridge waveguide. (a) The SiO_2 buffer layer is formed on the silicon substrate by thermal oxidation. (b) Deposition of ZnO thin film on an SiO_2 buffer layer by FCVA. (c) Deposition of line masks on the ZnO thin film for the preparation of plasma etching. (d) Formation of ridge waveguide after plasma etching and removal of photoresist.

the proposed dimensions of the ZnO ridge waveguide will favor TE mode operation.

III. FABRICATION AND CHARACTERIZATION OF ZnO RIDGE WAVEGUIDES

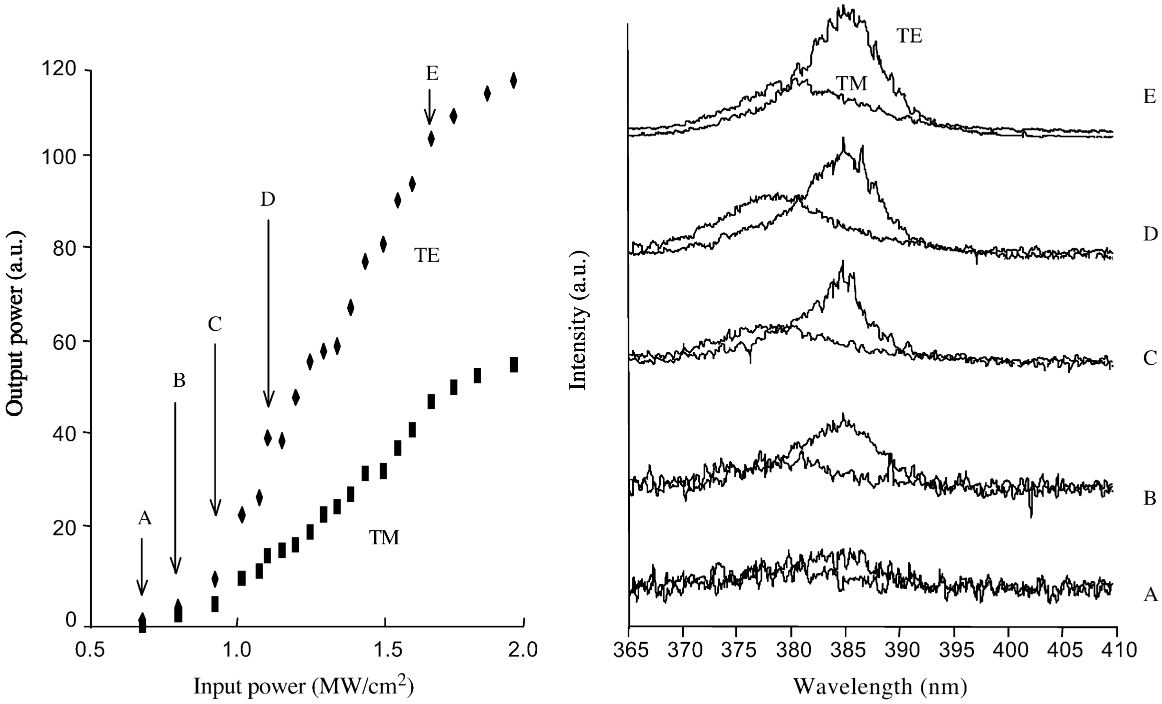
The fabrication procedures (see also Fig. 4) of the proposed ZnO ridge waveguides are described as follows.

- An SiO_2 buffer layer of thickness ~ 0.42 μm is formed on the surface of the n-type (100) silicon substrate by thermal dry oxidation for ~10 h at 1000 °C [12].
- A ZnO thin film of thickness $\sim$ 0.16 μm is deposited on the SiO_2 buffer layer by the FCVA technique with a substrate temperature and O_2 partial pressure of 230 °C and $\sim 2 \times 10^{-4}$ Torr, respectively [10].
- Pattern photoresist stripes, which have widths of 2 μm and a separation of $\sim$ 500 μm, are formed on the surface of the ZnO thin film by the photolithography technique.
- The unmasked region of ZnO thin film is partially etched by the plasma-enhanced chemical vapor deposition (PECVD) technique. The working pressure of the PECVD is $\sim 45 \times 10^{-4}$ Torr and the sample is exposed to $10H_2/20CH_4/5Ar$ plasma (where the numbers represent the gas flow in standard cubic centimeters per minute) [13]. In addition, the substrate is self-biased to ~ -300 V and the RF power is held constant at ~120 W. A magnetic field is also applied perpendicular to the ZnO thin film in order to increase the surface plasma density. Using these settings, the etch rate of ZnO by PECVD is ~6 nm/min.

As a result, ridges of $w_r \sim 2$ μm and $d_r \sim 0.1$ μm are obtained on the ZnO thin film.

The as-grown sample (i.e., without ridge structure) is examined under optical excitation by a frequency-tripled Nd:YAG laser (355 nm) at pulsed operation (6 ns, 10 Hz). In order to obtain lateral confinement of light inside the ZnO thin film, a cylindrical lens is used to focus the beam to form a line or a pumping stripe on the surface of the sample. The length and width of the pumping stripe are about 0.9 cm and 8 μm, respectively. Hence, a gain-guiding structure, which confines light along the lateral direction, is realized. Fig. 5 shows the light–light curves and the emission spectra of both TE and TM modes at different pump intensities. Spectra of ASE are observed from the edge of the waveguide through a polarizer in the direction perpendicular (TE) and parallel (TM) to the lateral direction. As we expected, the ZnO thin-film waveguide favors TE modes, and TM modes are strongly suppressed. It is also confirmed that our waveguide interfaces (i.e., between ZnO and SiO_2 as well as SiO_2 and Si) are smooth enough to minimize scattering loss so that high-intensity ASE can be sustained at low pump intensity. Fig. 6 captures the far-field profiles of both polarizations at high pump intensity ($\sim$ 1.3 MW/cm^2) from the as-grown samples. It is observed that the two polarizations emit at two different angles due to the roughness of the facets. Both polarizations exhibit one bright spot, which indicates that only fundamental TE and TM modes are supported by the samples, but the TE mode has a much higher intensity than that of the TM mode.

The measurement given in Fig. 5 is repeated for the samples with ridge structure on the ZnO thin films. The corresponding light–light curves and emission spectra of both TE and TM modes at different pump intensities are shown in Fig. 7. Again, the optical pumping is achieved by using the cylindrical lens to focus a pumping stripe on the ridge structure. However, the lateral confinement of the signal field is maintained by the ridge structure rather than the pumping stripe. From Figs. 5 and 7, it is noted that the device with ridge structure has demonstrated higher saturation power and lower threshold pump intensities for both polarizations than that of the as-grown samples. This implies that our design of ZnO thin-film ridge waveguides on silicon substrates has successfully maximized the coupling coefficient as well as minimized the absorption loss in silicon substrate. This again confirmed that the FCVA technique could fabricate ZnO thin film on silicon substrate with device quality (i.e., permits further processing such as etching or re-growth), which allowed the realization of more complicated devices structures. Fig. 8 captures the near- and far-field profiles of the TE modes



(a) (b)

Fig. 5. (a) Light–light curves for the two polarizations of the ZnO thin-film waveguide without ridge structure. (b) Corresponding emission spectra of the two polarizations at varying pump intensities.

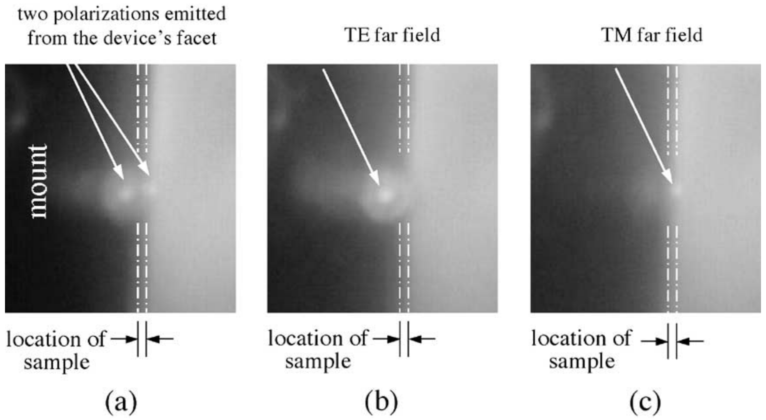


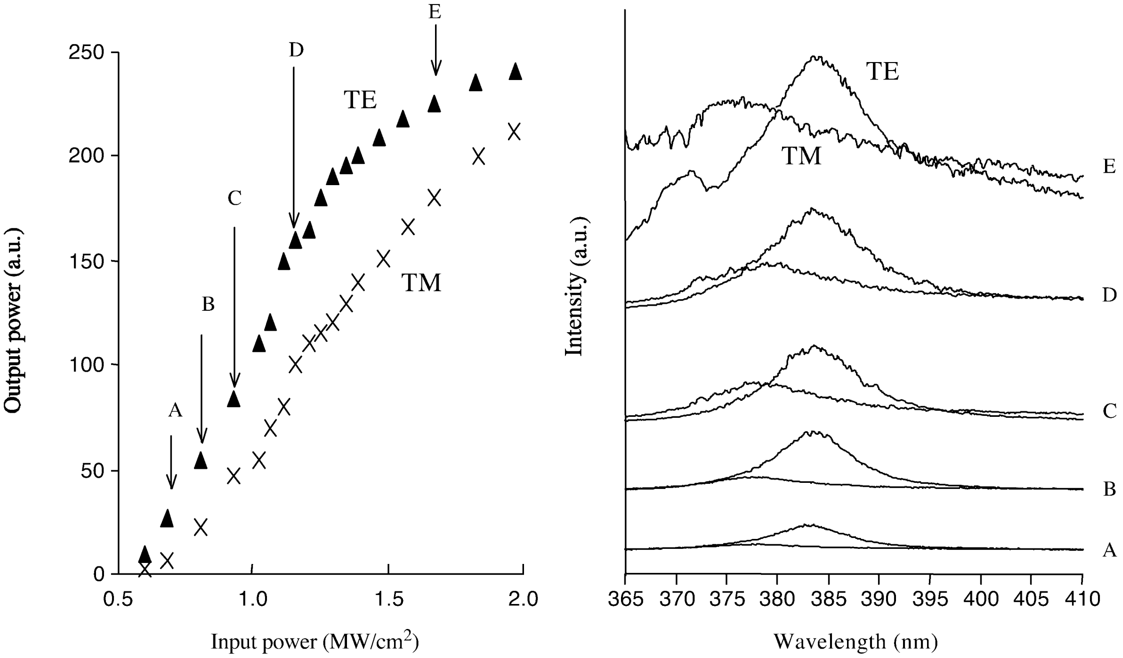
Fig. 6. (a) Far-field profiles of both polarizations under high-intensity excitation ($\sim$ 1.3 MW/cm^2). (b) and (c) Far-field profiles of TE and TM modes, respectively. The dotted–dashed lines indicate the location of the sample.

at low ($<$ 0.5 MW/cm^2) and high ($\sim$ 1.0 MW/cm^2) pump intensities, respectively, of the ZnO thin-film ridge waveguides. In the near-field experiment, the sample is exposed by a spot light with diameter of 9 mm so that several ridges are excited simultaneously. In the far-field experiment, a pumping stripe 8 μm wide is illuminated on one of the ridges. It is clearly observed that there is only one bright spot inside the ridge structure over the range of excitation intensities.

In Figs. 5 and 7, it is also observed that the emission spectra of both polarizations span between 375–395 nm. This implies that the mechanisms of optical gain are due to the composition of exciton–exciton scattering and electron–hole plasma (EHP) recombination but the optical gain is mostly dependent on the EHP recombination process. The net optical gain of the ZnO thin-film waveguides can be measured by the variable stripe length (VSL) method [14]. If L is the length of the pumping stripe and I_{tot} is the total detected intensity from the facet of the ZnO thin-film waveguide, then the corresponding net optical gain G can be obtained from the classical VSL equation as follows:

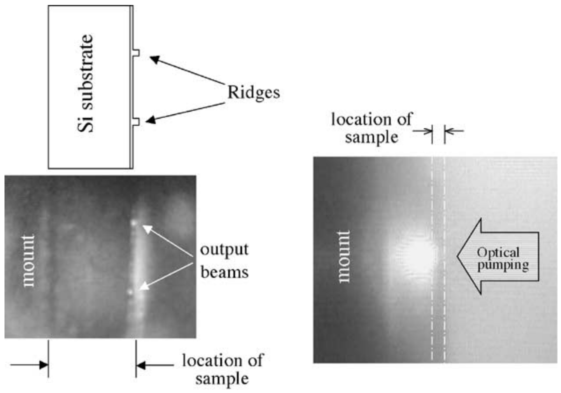
$$I_{\text{tot}}(L,\lambda) = \frac{I_{\text{sp}}(\lambda)}{G(\lambda)}\left[\exp\left(G(\lambda)\cdot L\right) - 1\right] \quad (3)$$

where I_{sp} is the spontaneous emission and λ is the wavelength of the net optical gain to be measured. Therefore, if the optical intensity output from the waveguides at a particular wavelength is measured with different lengths of the pumping stripe, then the corresponding net optical gain of both polarizations



(a) (b)

Fig. 7. (a) Light–light curves for the two polarizations of the ZnO thin-film waveguide with ridge structure. (b) Corresponding emission spectra of the two polarizations at vary pump intensities.



Near Field (TE) Far Field (TE)

(a) (b)

Fig. 8. (a) Near field of the TE mode under low-intensity excitation. (b) Far field of the TE mode under high-intensity excitation. The dotted–dashed lines indicate the location of the sample.

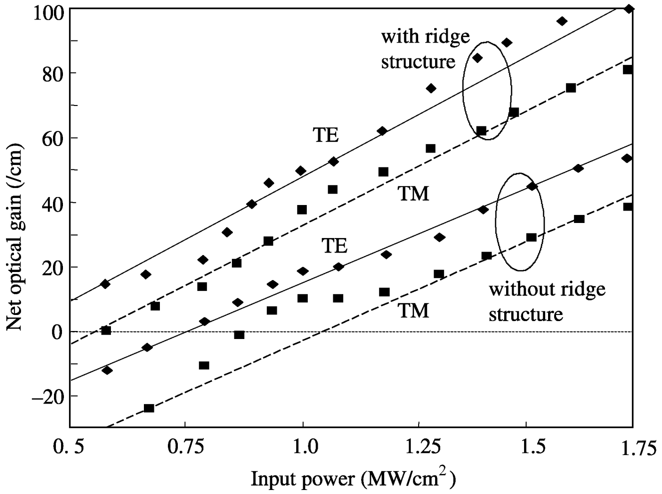
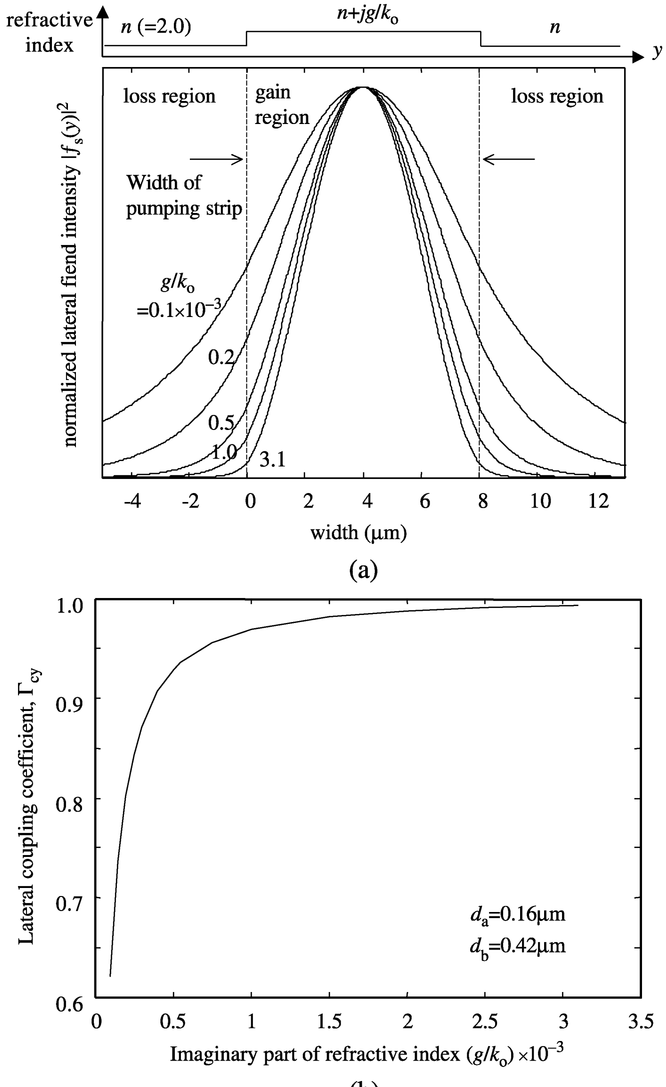


Fig. 9. Plot of net optical gain versus the pump intensities for both polarizations for the sample with and without ridge structures.

versus pump intensities at wavelength of peak optical gain can be deduced. It is observed that, for the sample with a ridge structure, the corresponding TE and TM net optical gains are about twice the magnitude compared to that of the as-grown one. The maximum net optical gain of TE polarization can go up to $\sim$ 120 cm^{-1} at a pump intensity of $\sim$ 1.9 MW/cm^2 for that with a ridge structure, but further increases of pump intensity will cause optical damage to the waveguides.

Furthermore, the net optical gain of the samples with ridge structure remains greater than zero over the range of pump intensities. This is because the corresponding value of Γ_c remains greater than 0.9. However, for the as-grown sample, the net optical gain can be negative at low pump intensities as Γ_c reduces below 0.9. This can be explained by the dependence of Γ_{cy} on the optical gain inside the region of pumping stripe of the as-grown samples. Fig. 10(a) plots $|g_s(y)|^2$ versus the imaginary part of refractive index (i.e., g/k_o, where g is the optical gain inside the pumping stripe and $k_o = 2\pi/\lambda$) inside the pumping stripe region. $g_s(y)$ is calculated under the assumption that the pumping stripe forms a gain-guiding structure to confine the lateral field inside the pumping stripe region. Fig. 10(b) shows the variation of Γ_{cy} with g/k_o of a ZnO thin-film waveguide with $d_a = 0.16$ μm and $d_b = 0.42$ μm. This implies that if g is not high enough, the lateral field will extend into the unexcited region (i.e., high absorption region) so that the net optical gain can be a negative value.



(a)

(b)

Fig. 10. (a) Plot of lateral field profiles for different optical gain inside the region of pumping stripe. n and g/k_o are the real and imaginary parts of the refractive index. (b) Plot of lateral coupling coefficient Γ_{cy} versus the imaginary parts of the refractive index inside the region of pumping stripe g/k_o.

IV. DISCUSSION AND CONCLUSION

If Fabry–Perot cavities can be formed by our proposed ZnO thin-film ridge waveguides with field reflectivity at facets greater than 0.01 and have a cavity length of 500 μm, then the required net optical gain to reach round-trip gain condition is about 50 cm^{-1}. This implies that UV lasing should be easily realized in our devices. However, only high-intensity UV ASE is observed from our ZnO thin-film waveguides. This is because the two facets of the waveguides are too rough to provide enough optical feedback to achieve lasing. In fact, it is very difficult to obtain natural cavity in ZnO thin films by cleaving as in the case of (100) GaAs or InP semiconductor materials. Furthermore, our ZnO thin-film waveguides have no self-assembled hexagonal microcrystallites (i.e., natural Fabry–Perot microcavities) to provide distributed optical feedback to sustain lasing like those that grow on sapphire substrates [6], [7]. Additional research is currently underway to overcome this problem, and the results of this research will be published elsewhere.

In conclusion, the feasibility of fabricating ZnO thin-film waveguides on silicon substrates has been demonstrated by using the FCVA technique at a low deposition temperature ($\sim$ 230 °C). The advantages of using the FCVA technique are: 1) the possibility of depositing device-quality ZnO thin films on lattice-mismatched silicon substrates; 2) low-temperature process; and 3) the ability to be scalable to large-area substrates (up to 8″ in diameter in our system). It is shown that our ZnO thin-film waveguides exhibit low pump threshold ($\sim$ 0.5 MW/cm^2) and high-intensity UV ASE. The maximum net optical gain that can be achieved is about 120 cm^{-1} at pump intensity of 1.9 MW/cm^2. If we take into consideration the surface roughness, optical leakage, and free carrier absorption as the total losses of our proposed waveguides, its optical performance is in fact comparable to that fabricated on sapphire. Therefore, we have proved that lattice-mismatching is not the major problem to realizing UV ZnO lasing devices on silicon. Furthermore, the significance of using the FCVA technique in the fabrication of the emerging UV optoelectronics has been demonstrated.

REFERENCES

[1] Y. Chen, H. J. Ko, S. K. Hong, and T. Yao, "Simulated emission and optical gain in ZnO epilayers grown by plasma-assisted molecular beam epitaxy with buffer," *Appl. Phys. Lett.*, vol. 79, no. 11, pp. 1469–1471, 2001.

[2] D. M. Bagnll, Y. F. Chen, Z. Zhu, T. Yao, M. Y. Shen, and T. Goto, "High temperature excitonic stimulated emission from ZnO epitaxial layers," *Appl. Phys. Lett.*, vol. 73, no. 8, pp. 1038–1040, 1998.

[3] P. Fons, K. Iwata, S. Niki, A. Yamada, and K. Matsubara, "Growth of high-quality epitaxial ZnO films on $\alpha - Al_2O_3$," *J. Cryst. Growth*, vol. 201, pp. 627–632, 1999.

[4] S. Muthukumar, J. Zhong, Y. Chen, Y. Lu, and T. Siegrist, "Growth and structural analysis of metalorganic chemical vapor deposited (1120) $Mg_xZn_{1-x}O$ $(0 < x < 0.33)$ films (0112) on R-plane Al_2O_3 substrates," *Appl. Phys. Lett.*, vol. 82, no. 5, pp. 742–744, 2003.

[5] S. Bethke, H. Pan, and B. W. Wessels, "Luminescence of heteroepitaxial zinc oxide," *Appl. Phys. Lett.*, vol. 52, pp. 138–140, 1988.

[6] Z. K. Tang, G. K. L. Wong, P. Yu, M. Kawasaki, A. Ohtomo, H. Koinuma, and Y. Segawa, "Room temperature ultraviolet laser emission from self-assembled ZnO microcrystallite thin films," *Appl. Phy. Lett.*, vol. 72, no. 25, pp. 3270–3272, 1998.

[7] M. Kawasaki, A. Ohtomo, I. Ohkubo, H. Konuma, Z. K. Tang, P. Yu, G. K. L. Wong, B. P. Zhang, and Y. Segawa, "Excitonic ultraviolet laser emission at room temperature from naturally made cavity in ZnO nancrystal thin films," *Mat. Sci. Eng. B*, vol. 56, pp. 239–245, 1998.

[8] X. Q. Wang, S. R. Yang, X. T. Yang, D. Liu, Y. T. Zhang, J. Z. Wang, J. Z. Yin, D. L. Liu, H. C. Ong, and G. T. Du, "ZnO thin film grown on silicon by metal-organic chemical vapor deposition," *J. Cryst. Growth*, vol. 243, pp. 13–18, 2002.

[9] M. Ohtsu, K. Kobayashi, T. Kawazoe, S. Sangu, and T. Yatsui, "Nanophotonics: design, fabrication, and operation of nanometric devices using optical near field," *IEEE J. Select. Topics Quantum Electron.*, vol. 8, pp. 839–862, July/Aug. 2002.

[10] X. L. Xu, S. P. Lau, J. S. Chen, G. Y. Chen, and B. K. Tay, "Polycrystalline ZnO thin films on Si(100) deposited by filtered cathodic vacuum arc," *J. Cryst. Growth*, vol. 223, p. 201, 2001.

[11] M. J. Adams, *An Introduction to Optical Waveguides*. New York: Wiley, 1981.

[12] S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed. New York: Wiley, 1981.

[13] K. Ip, K. H. Baik, M. E. Overberg, E. S. Lambers, Y. W. Heo, D. P. Norton, S. J. Pearton, F. Ren, and J. M. Zavada, "Effect of high-density plasma etching on the optical properties and surface stoichiometry of ZnO," *Appl. Phys. Lett.*, vol. 81, no. 19, pp. 3546–3548, 2002.

[14] J. Velenta, I. Pelent, and J. Linnros, "Waveguiding effects in the measurement of optical gain in a layer of Si nanocrystal," *Appl. Phys. Lett.*, vol. 81, no. 8, pp. 1396–1398, 2002.

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