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Demonstration of a visible laser on silicon using Eu-doped GaN thin films

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We report the demonstration of *visible* laser action on silicon. We have utilized Eu-doped GaN for the active medium within a structure consisting of multiple AlGaN layers grown by molecular-beam epitaxy on a Si substrate. Stimulated emission was obtained at room temperature from Eu^{3+} at 620 nm, with a threshold of $\sim$117 kW/cm^2. Values of modal gain and loss of $\sim$100 and 46 cm^{-1} were measured. This demonstration indicates that utilizing rare earths a range of lasers on Si can be obtained, covering the UV, visible, and IR regions, thus enabling a significant expansion of optoelectronic and microelectronic integrations. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2037867]

The use of light for improving the performance and flexibility of silicon microelectronics has been an elusive goal for many years. Conventional Si (as used in microelectronics) is not a suitable light-emitting material since it has an indirect band gap and significant absorption at visible wavelengths. Therefore, a variety of Si modifications and combinations with other materials that are better light emitters are being investigated.[1] Recently, lasing on Si-on-insulator (SOI) substrates has been reported[2,3] at infrared (IR) wavelengths (1.67 μm) using the stimulated Raman scattering (SRS) effect by optical pumping (at 1.54 μm). Electrically pumped SRS lasing at IR wavelengths ($\sim$9 μm) has been very recently reported[4] in compound semiconductor (InGaAs/InAlAs) heterostructures grown by molecular-beam epitaxy (MBE) on InP substrates and operated at low temperatures. This combination of results naturally leads to the consideration of obtaining lasing on Si by the heterogenous integration of compound semiconductors on Si substrates. To produce lasing at visible wavelengths by this approach requires the use of wide band-gap semiconductors such as the III-N family (GaN/AlN/InN). Previously, lasing from GaN-on-Si structures has been reported[5,6] at ultraviolet (UV) wavelengths (368 nm) by optical pumping (at 337 nm). Here we report the demonstration of *visible* laser action on silicon. We have utilized Eu-doped GaN for the active medium within a structure consisting of multiple AlGaN layers grown by MBE on a Si substrate. Stimulated emission (StE) was obtained at room temperature from Eu^{3+} at 620 nm, with a threshold of $\sim$117 kW/cm^2. The values of modal gain and loss of $\sim$100 and 46 cm^{-1} were measured. This demonstration indicates that a range of rare-earth- (RE) based lasers on Si can be obtained, covering the UV, visible, and IR regions, thus enabling a significant expansion of optoelectronic and microelectronic integrations.

RE-based light emitters are very versatile, being utilized in many applications[7] ranging from fiber-optic amplifiers to solid-state lasers to display phosphors. Excited rare-earth elements[8] (such as Eu, Er, Tm, and Tb) exhibit sharp emission lines from the UV to the near IR. In general, since these are inner-shell (usually intra-4*f*) transitions the emission wavelengths vary only slightly with the host and are nearly completely temperature independent. The excitation efficiency and emission linewidth do depend on the quality (primarily crystallinity) of the host material. The III-N family of wide band-gap semiconductors (primarily GaN and AlGaN) has been shown[9] to be excellent hosts for RE emission. We have recently reported[10] the evidence for stimulated emission from Eu-doped GaN structures fabricated on sapphire substrates. The growth of GaN structures lacks a native substrate, with sapphire and SiC being the most widely utilized alternatives. The growth of high-quality GaN thin films on Si substrates has obvious advantages of scale, cost, and the promise of revolutionary increase in functionality. However, to be successful GaN-on-Si heteroepitaxy has to overcome the twin challenges of lattice and thermal-expansion mismatch. We have utilized Si (111) substrates,[11] which incorporated[12] several AlGaN and AlN thin films as buffer, strain compensation, and bottom optical cladding layers. A 0.5-μm GaN active layer doped with $\sim$1-at. % Eu and an AlGaN top cladding layer were grown on the Si substrates. The entire structure forms a planar waveguide.

To demonstrate laser action, we used optical pumping with a pulsed N_2 laser ($\lambda = 337.1$ nm, 600-ps pulse). The laser beam was incident on the top surface of the waveguide structure and the edge emission was collected to analyze the characteristics of emitted light. Fig. 1 shows the Eu (red) edge emission under pumping conditions of 8 MW/cm^2. The red emission is due to the dominant intra-4*f* transition ($^5D_0 \rightarrow {}^7F_2$) of trivalent Eu^{3+} ions. The peak emission wavelength is 620 nm, which is the same as that obtained[9] from GaN:Eu stimulated emission on sapphire substrates. GaN:Eu grown directly on conventional Si substrates exhibits[13] spontaneous emission at 621 and 623 nm under optical and electrical excitations, respectively.

The edge emission displays the properties of stimulated emission, including strong gain, threshold effect, polarization dependence, and emission line narrowing. The variable stripe length[14] (VSL) and shifting excitation spot[15] (SES) tech-

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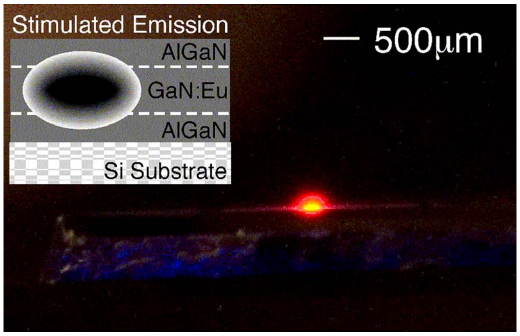

FIG. 1. (Color online) Stimulated emission from the edge of the GaN:Eu on Si Lasing structure. Insert shows cross section of the structure.

niques were used to obtain gain and loss properties, respectively.

As shown in Fig. 2, the modal gain was measured as a function of pump peak power density using the VSL technique. At pump power levels above a certain threshold level, StE and positive gain values are obtained. In our measurements, gain increases linearly with pump power up to a few $\mathrm{MW/cm^2}$, beyond which gain saturation is observed. The maximum gain measured is $\sim 95\ \mathrm{cm^{-1}}$ at $8\ \mathrm{MW/cm^2}$. Using curve fitting in the linear gain region, we have extrapolated the pump power threshold for StE of $\sim 117\ \mathrm{kW/cm^2}$. Below threshold, spontaneous emission (SpE) is observed and negative gain values are measured, indicating that in this pump power regime the VSL technique measures the waveguide loss in the structure.[16] The negative gain values ($\sim 50\ \mathrm{cm^{-1}}$) measured by VSL are comparable to those obtained from SES loss measurements ($\sim 46\ \mathrm{cm^{-1}}$).

In contrast to amplified spontaneous emission, stimulated emission can be identified by several properties, including polarization of emission, spectral line narrowing, and resonant-cavity modes. Figure 3 shows that emission from a Eu-doped GaN planar waveguide possesses all the characteristics of laser action. The spectra contained in Fig. 3(a) indicate the polarization dependence of the stimulated edge emission above threshold ($\sim 8\ \mathrm{MW/cm^2}$). The laser emission is polarized in the plane of the active layer, with the TE mode emission being $\sim 10\times$ higher than the TM mode emission. Figure 3(b) shows the emission spectral linewidth as a function of input peak power density. The FWHM (full width at half maximum) of the emission peak below threshold is ~ 2.3 nm, dropping to ~ 1.9 nm above threshold. Finally, Fig. 3(c) contains a high-resolution spectrum from the Eu-doped GaN planar waveguide structure having a 350-μm cavity length. Above threshold ($\sim 73 I_{\mathrm{th}}$), an emission spectrum with a well-defined mode structure is observed. The spectrum has peaks evenly spaced at 4 Å, clearly indicating resonant-cavity modes. The measured FWHM of each mode is ~ 2 Å, which is limited by the resolution of our spectrom-

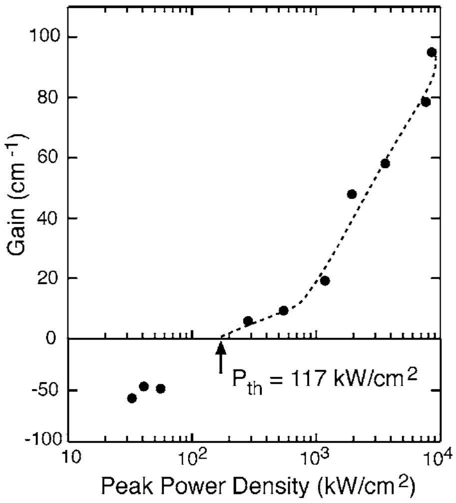

FIG. 2. Gain and loss as a function of peak pump power density for a GaN:Eu on Si laser structure.

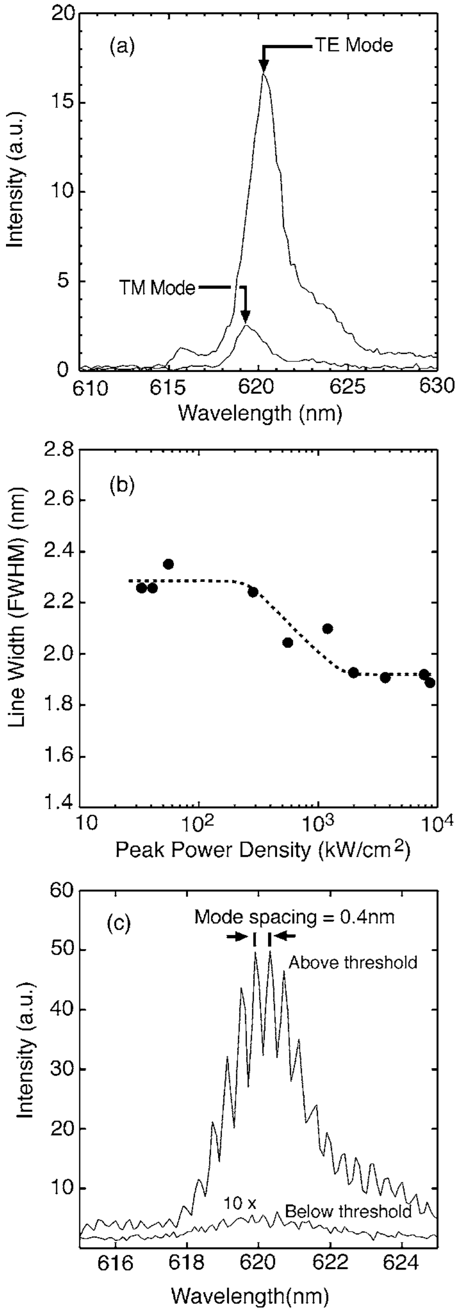

FIG. 3. Lasing properties of edge emission from GaN:Eu structure on Si: (a) polarization dependence of stimulated edge emission spectra above threshold; (b) spectrum line (FWHM) narrowing effect; and (c) high-resolution spectrum of edge emission from the 350-μm-long cavity below and above threshold.

eter. The emission spectrum below threshold ($\sim 0.3 I_{\mathrm{th}}$) exhibits no resonant modes. We have also observed ~5.6-Å mode spacing in the emission spectrum of a shorter cavity (145 μm). This corresponds to the free spectral range of this cavity. The FWHM of the evenly spaced peaks is ~2.5 Å. The combination of all these StE-related factors demonstrates the presence of visible lasing action on silicon.

In summary, an optical cavity was formed on Si substrates by growing *in situ* Eu-doped GaN thin films, with $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}$ films (of various compositions) serving as cladding and transition layers. The StE threshold for optical pumping of a ~1-at.% Eu-doped GaN sample is ~117 kW/cm^2. The StE threshold is accompanied by reductions in the emission linewidth and significant polarization dependence of the edge emission. The best values of modal gain and loss obtained to date on Si are ~100 and 46 cm^{-1}, respectively. We believe that this successful demonstration of visible laser action on Si could open the way toward the fabrication of Si photonics chips, which will integrate on a single Si substrate a range of visible and infrared sources, conventional waveguide structures, and Si detector technology.

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