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Semiconductor nanowire laser and nanowire waveguide electro-optic modulators

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Electric field modulation of visible and ultraviolet nanoscale lasers consisting of single CdS or GaN nanowires has been achieved using integrated, microfabricated electrodes. Modulation of laser emission intensity is achieved with no detectable change in the laser wavelength. The devices can also be operated below the lasing threshold to modulate the intensity of light propagating within the nanowire waveguide. Studies of the electric field dependence in devices of varied geometry indicate that modulation is due to an electroabsorption mechanism. These findings expand opportunities for multicolor, nanowire-based photonic devices and circuits. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2089157]

Semiconductor nanowires (NWs) are emerging as promising building blocks for nanoscale photonic devices and circuits.[1–8] NWs have been utilized as key elements in single and multicolor nanoscale light-emitting diodes (nanoLEDs),[2–4] polarization sensitive photodectors,[5] and optically- and electrically-driven lasers,[8–10] in which single NWs both define the optical cavity and are the active lasing medium. Recent studies have also shown that CdS NWs can function as efficient waveguides capable of guiding light through subwavelength bends with low losses. Optical signals also have been launched in the CdS NW waveguides using either direct optical excitation or integrated NW nanoLEDs,[6] and preliminary measurements also have shown that transmission through CdS NW waveguides can be attenuated with an applied electric field.[6] These latter results suggests the possibility of integrating electro-optic modulators (EOMs) directly on the NW waveguides.

EOMs are frequently used to switch the output of semiconductor lasers, for example in data transmission applications.[11] EOMs are generally preferable to direct laser diode modulation because modulation of the intensity occurs without changes in laser frequency (chirp),[11] and because higher speeds are typically possible due to reduced lead inductance and capacitance. In this letter, we report the integration of EOMs on NW laser cavities and the first demonstration of electric field modulation of lasing in both CdS and GaN single NW lasers. In addition, experiments conducted below threshold on nanowire EOM devices fabricated with different geometries support an absorption-based mechanism for modulation.

CdS and GaN NWs were grown using nanocluster-catalyzed metal-organic chemical vapor deposition (MOCVD) or nanocluster-directed pulsed laser deposition methods reported previously.[12–14] The NWs used in these studies were single crystalline with diameters of ~100 nm and lengths >10 μm. EOM devices with a parallel-plate structure [Fig. 1(a)] were used to apply a uniform electric field over a length L of the NW. Band-edge light is launched into guided modes of the waveguide by direct excitation of the NW with an diffraction-limited laser ~5 μm from the modulator top electrode, and the spectrum and intensity of light emitted from the end of the NW is then recorded while a time-varying voltage signal is applied to the electrodes.[15]

Measurements of electric field modulation of CdS NW lasers were conducted at 4.2 K, where lasing is associated with the exciton line near 489 nm.[10] Figure 1(b) shows the modulation of the output spectrum of a representative CdS NW-EOM with L=6 μm and SiO_2 dielectric thicknesses $t_{top}=t_{bot}=50$ nm. The device is operated just above the lasing threshold in order to allow direct comparison between the response of the exciton lasing line and spontaneous emission from the free electron-bound hole (FEBH) feature at ~514 nm. Variation of the applied voltage, V, from 0 to 30 V, shows that the exciton lasing line is significantly attenuated, with no resolvable shift in the peak wavelength, while the FEBH features shows a much smaller attentuation. For a given wavelength and V, the modulation, M, is given by (I_{ON}/I_{OFF})-1, where I_{ON} and I_{OFF} are the intensities with and without V. Plots of M vs V for both the exciton lasing line and FEBH feature [Fig. 1(c)] exhibit a linear dependence on V over the ±50 V range tested. Notably, the 489 nm lasing line is modulated by 40% at 45 V, which is >2× the modulation of the FEBH feature.

In addition, we fabricated and studied EOM devices using GaN NWs. The laser spectrum shown in Fig. 2(a) is characterized by multimode emission with a dominant peak at 373 nm. Intensity modulation is accomplished without a change in the peak positions as the applied voltage is varied. Detailed measurements of M vs V [Fig. 2(b)] carried out below the lasing threshold show that the end emission intensity varies linearly with voltage over the ±45 V range studied. Significantly, these results show that modulation of at least 20% can be readily achieved above or below the threshold for lasing in these GaN NW EOMs.

To probe the physical mechanism of modulation in the NW cavities, we have investigated EOMs based on two different device geometries [Fig. 3(a)]. The first approach is the parallel-plate capacitor scheme described above; in the second, a NW on the substrate surface is subjected to the fringe field generated by a pair of electrodes fabricated alongside the NW. This alternate geometry was investigated to distinguish the electric-field response from other factors, such as electrostatic pressure and charge transfer. Both EOM geometries, which were studies at room temperature and low ex-

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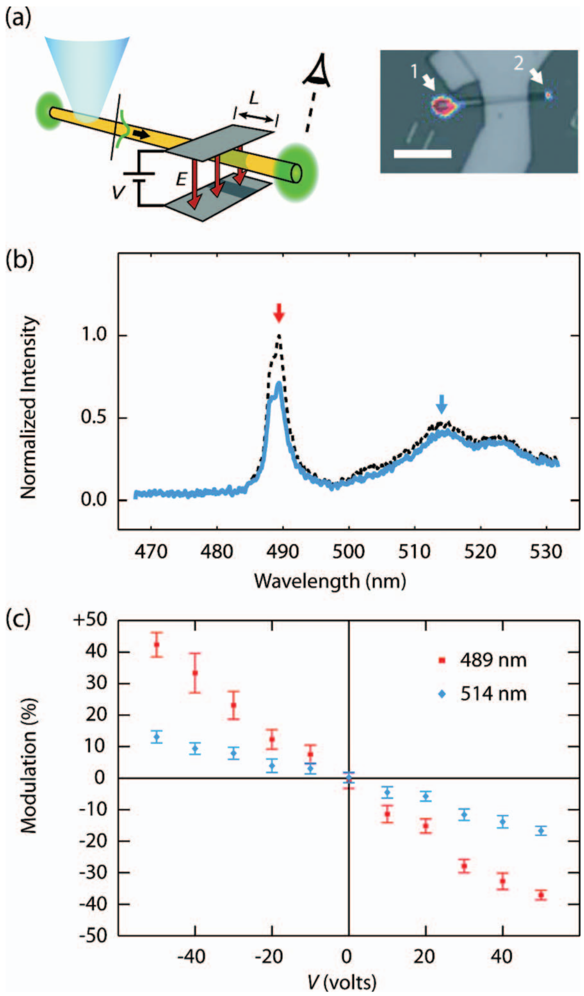

FIG. 1. (Color) (a) Diagram indicating the excitation site, region of field modulation, and observed NW end. At right, superimposed PL image (recorded below laser threshold) and white-light optical micrograph of a representative CdS NW EOM-laser device. Numerals 1 and 2 indicate excitation site and observed NW end, respectively. Scale bar, 5 μm. (b) Emission spectra of a CdS NW laser showing effect of a 30 V signal. (c) Modulation M vs V at the two indicated wavelengths for the EOM-laser in (b). Error bars reflect the standard deviation of the responses to 50 square-wave pulses at 0.5 Hz.

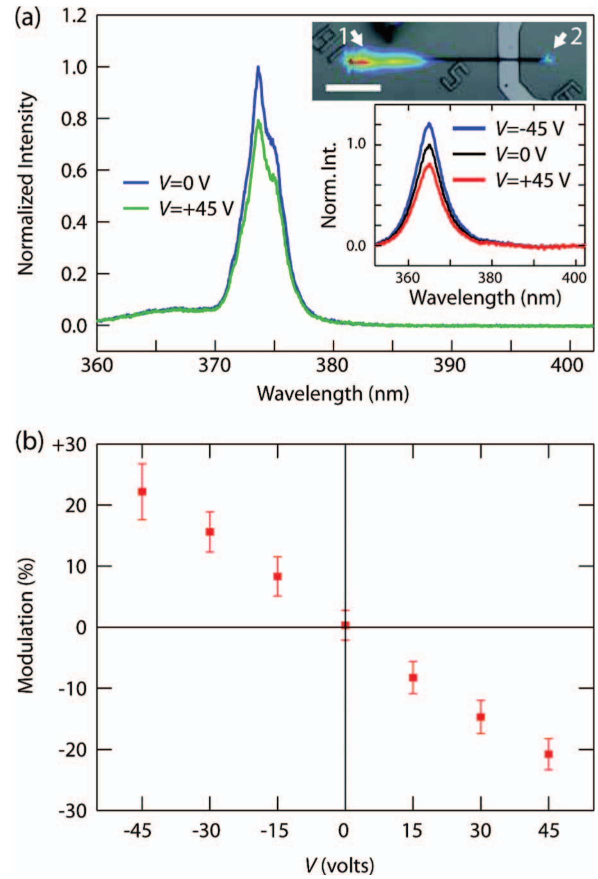

FIG. 2. (Color) (a) GaN NW emission spectrum above lasing threshold, with and without bias applied. Insets, recorded below threshold: top, superimposed PL and white-light image of device; scale bar is 10 μm. Bottom, end emission spectra at three different bias values. (b) M vs V, below threshold. For this device, $t_{top}=100$ nm, $t_{bot}=50$ nm. All data were recorded at room temperature.

citation powers, exhibited linear M-V response for $|V| < 25$ V. The modulation does not depend on the ground referencing of the applied voltage, and no modulation is observed if the same voltage is applied to both plates (which varies the potential, but not the field). Figure 3(b) presents the length-normalized modulation, M/L, for five representative devices. For each of the five devices, a finite element analysis model was used to calculate the field strength at the voltages tested. The results show that M scales linearly with electric field and L.

Intensity modulation in semiconductor EOMs is generally achieved either by modulation of the absorption coefficient or by using a phase- or polarization-sensitive element to detect modulation of the refractive index n.[11,16] Both mechanisms are potentially relevant to the NW EOMs since (1) waveguided light is close in energy to the band gap and thus sensitive to field-induced changes in the absorption spectrum, and (2) the NW ends are subwavelength scattering centers which may yield a change in the intensity for a change in n. However, refractive effects cannot be the sole origin of modulation because for a typical NW EOM device ($L \sim 5$ μm) the phase shift will be less than 0.003π at 25 V/μm using the electro-optic coefficients for CdS.[17]

Electroabsorption studies in both CdS and GaN thin films have suggested deviations from the free-carrier Franz-Keldysh effect for near band-edge wavelengths due to excitonic effects in these materials. At 4.2 K, the strongest modulation in CdS thin films was associated with the I_1 exciton absorption line at 489 nm—the same wavelength as the emission peak of our CdS nanowire EOM-laser.[18] More recently, exciton absorption in GaN films has been investigated for use in electro-optic modulator devices at room temperature.[19] While the Franz-Keldysh effect and related electroabsorption phenomena are intrinsically independent of field polarity, an asymmetric response is frequently observed in semiconductors having internal electric fields, e.g., in quantum well modulators.[20] In the CdS and GaN NWs studied here, a substantial internal field normal to the substrate could arise because the c axes of the uniaxial wurtzite crystals are oriented orthogonally to the growth axes of the NWs, such that opposite sides of the NW have differing atomic structure and polarity.[21–23] Electric field-modulated absorption, offset by a large internal field, could explain our observed results, and thus represents a plausible mechanism for modulation in CdS and GaN nanowire waveguides and lasers.

In conclusion, these studies demonstrate the fabrication of the first EOMs integrated on NW lasers. Our studies show

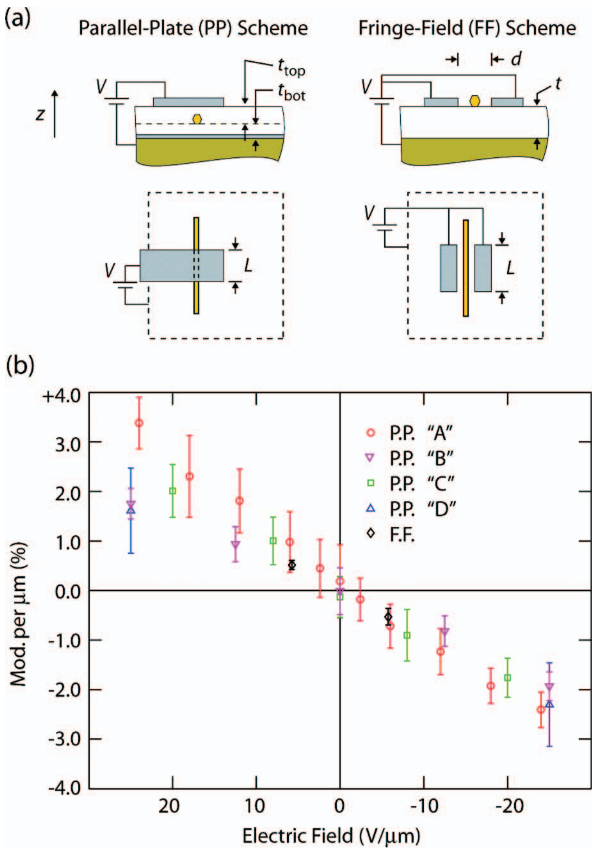

FIG. 3. (Color) (a) Two schemes used to apply electric fields. (b) Length-normalized modulation (M/L) for representative parallel-plate (PP) and fringe-field (FF) devices. PP: "A," $L=10$ μm, $t_{top}=100$ nm, $t_{bot}=600$ nm; "B," $L=4$ μm, $t_{top}=100$ nm, $t_{bot}=220$ nm; "C," $L=8$ μm, $t_{top}=100$ nm, $t_{bot}=50$ nm; "D," $L=4$ μm, $t_{top}=160$ nm, $t_{bot}=160$ nm. FF: $L=12$ μm, $t=600$ nm, $d=2$ μm. Note that a positive field corresponds to $V<0$.

substantial modulation is possible in both CdS and GaN NWs, and moreover, that an electro-absorption model provides a qualitative explanation for field-dependence measured in different geometries. A number of opportunities exist for the future. For example, it should be possible to extend these studies to NW-based EOMs devices operating over the ultraviolet through visible wavelengths using CdS, GaN, and related II-VI and III-nitride semiconductor alloy materials. In addition, electroabsorption spectroscopy of single NWs, including NWs with quantum-confined core-shell structures,[2] could provide details on exciton behavior in these systems and lead to enhanced modulation depth. In combination with other nanoscale optical components, NW EOM lasers and waveguides could serve as key devices required to enable multiplexed optical sensing, storage, or information processing.

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