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Hybrid structure laser based on semiconductor nanowires and a silica microfiber knot cavity

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We demonstrate a hybrid structure laser consisting of a single or multiple zinc oxide (ZnO) nanowires attached to a silica microfiber knot cavity, which is pumped by 355 nm wavelength laser pulses. The laser threshold is lower than 0.2 μJ/pulse. The measured linewidth of the lasing mode is about 0.04 nm. The hybrid structure combines advantages of high gain of semiconductor nanowires and high quality factor of microfiber knot cavities. Additionally, the design offers convenient and efficient approach to both pumping and collection of the semiconductor nanowire lasers. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3093821]

Semiconductor lasers based on cadmium sulfide (CdS), zinc oxide (ZnO), gallium nitride (GaN) nanowires, and gallium antimonide (GaSb) subwavelength wires have gained considerable attentions.[1–5] In previous studies, a semiconductor nanowire is not only a gain medium but also acts as a laser cavity. However, due to the small diameter of the nanowire and the existence of substrate, significant evanescent field exists outside the nanowire body that may introduce significant losses and limit the quality factor (Q factor).[6–9] Both theoretical and experimental works have shown the potential to achieve high Q factor optical cavities and low threshold lasers based on hybrid nanowire structures.[10–12] Compared with semiconductor nanowire cavities that usually have Q factors lower than 10^3, microfiber knot cavities with Q factors as high as 10^4–10^5 have been reported.[13,14] However, in previous work,[15] the attempts to produce a rare-earth doped microfiber knot laser with knot diameter below 1 mm failed due to the insufficient pump absorption or signal gain within the microscale knot. Here we report a hybrid laser combining a semiconductor nanowire gain section and a microfiber knot cavity. We integrate two components in a hybrid device to combine high gain of semiconductor nanowires and high Q factors of microfiber knot cavities.

The hybrid structure consists of single or multiple ZnO nanowires attached to a silica microfiber knot cavity (see Fig. 1). ZnO nanowires are synthesized via a chemical vapor transport process[16] and subsequently dispersed onto a MgF_2 substrate. Microfibers are fabricated using a flame-heated taper drawing of commercial all-silica fibers with 0.06 dB/m loss at 355 nm wavelength. We adopt the following approach to fabricate the hybrid structure. First, a microfiber knot is assembled by micromanipulation under an optical microscope,[14] and then a single ZnO nanowire is taken up from the substrate and moved toward the microfiber knot by home made fiber probes. When a section of the ZnO nanowire touches the microfiber, they attract each other by the van der Waals force or the electrostatic force. By careful manipulation, almost the whole nanowire can be attached to the microfiber knot [Fig. 1(a)]. This process can be repeated for making use of the second or third ZnO nanowire [Fig. 1(b)]. Finally, a second microfiber (tapered from a conventional fiber) is used to collect the output of the knot by means of evanescent coupling.

To operate the hybrid laser, a pump light is first sent into the input port by lens-focused launching, and then squeezed into microfiber and subsequently the knot structure through the taper, as shown in Fig. 1(c). When the attached ZnO nanowire is excited by evanescent waves outside the microfiber, ultraviolet photoluminescence (PL) [Fig. 1(c) upper inset] recirculates inside the knot cavity that leads to lasing action.

To investigate the lasing properties of the hybrid laser, a hybrid structure is assembled with a 350-nm-diameter ZnO nanowire and a 780-μm-diameter microfiber knot [Fig. 1(a)]. The pump laser is a frequency-tripled neodymium doped yttrium aluminum garnet (Nd:YAG) laser pulses (355 nm, 6 ns, and 10 Hz). Figure 2(a) shows the PL spectra of the hybrid

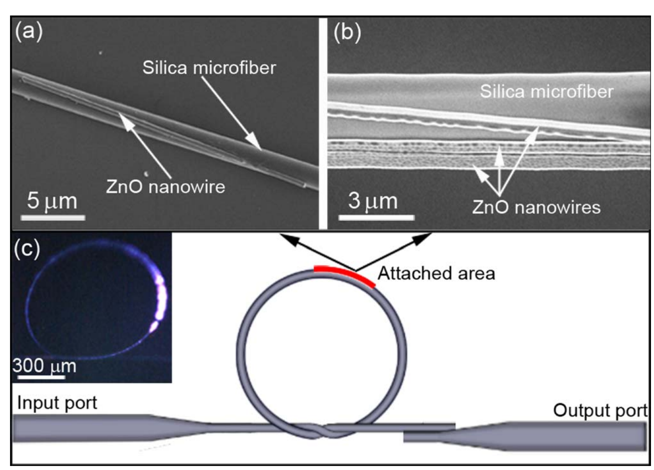

FIG. 1. (Color online) (a) Scanning electron microscope (SEM) image of attached area of a 25-μm-long 350-nm-diameter ZnO nanowire and a 780-μm-diameter microfiber knot assembled with a 1.8-μm-diameter silica microfiber. (b) SEM image of attached area of three ZnO nanowires and a 728-μm-diameter silica microfiber knot assembled with a 3.5-μm-diameter silica microfiber, the diameters of the ZnO nanowires are 500, 480, and 600 nm, respectively. (c) Schematic diagram of the structure of a hybrid laser. Upper inset, optical microscope image of the hybrid structure in (a) pumped by 355 nm wavelength laser pulses.

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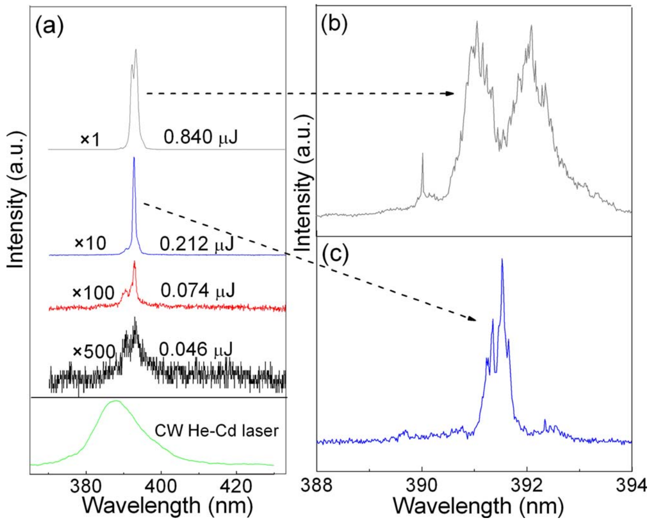

FIG. 2. (Color online) (a) Output spectra vs pump energy of the hybrid structure [the same structure shown in Fig. 1(a)]. (b) Close-up views of two laser spectra in (a).

structure at different pump intensities. As a comparison, the PL spectrum excited using a continuous wave helium-cadmium laser (325 nm) is also shown in the bottom trace of Fig. 2(a). The emission peak under low-power pulse laser excitation locates at the low energy shoulder of spontaneous emission excited by continuous waves and shows a narrower full width at half maximum, which may be attributed to the exciton-exciton collision effect.[17] When the pump power exceeds the threshold for laser oscillation, sharp peaks in the PL spectrum appear and the PL peak at the primary lasing wavelength abruptly increases, while the spectral width of the PL decreases. The output power is concentrated in a narrow emission range (391 nm $<\lambda<$ 392 nm). With the increasing power (pump level higher than 0.27 μJ/pulse), the laser emission range broadens and redshifts slightly. It may be attributed to heating, band gap renormalization, carrier-induced refractive index change, or the emergence of electron-hole plasma.[18,19]

Close-up views of two distinct laser spectra are shown in Figs. 2(b) and 2(c). The mode spacing measured from the lasing spectra in Fig. 2(b) is about 0.04 nm, corresponding to a calculated knot diameter of about 800 μm,[5] which is in good agreement with the measured effective cavity length of 780 μm. The small difference between the calculated and the measured values may be caused by the attached ZnO nanowires, as the calculation is based on the refractive index

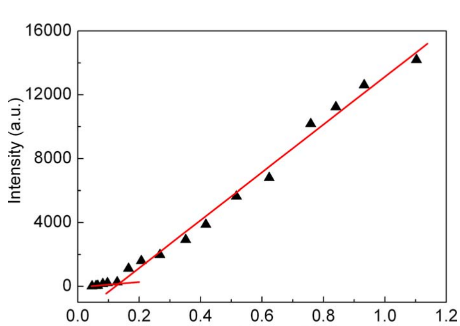

FIG. 3. (Color online) Integrated emission intensity vs pump energy of the hybrid structure [the same structure used in Fig. 1(a)].

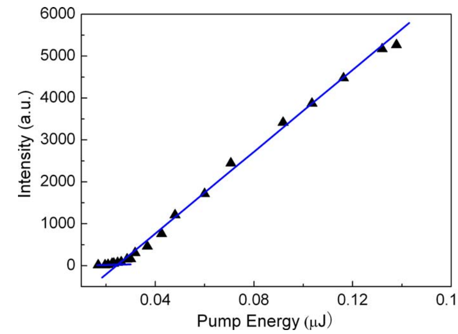

FIG. 4. (Color online) Integrated emission intensity vs pump energy of a hybrid structure with three ZnO nanowires [the same structure shown in Fig. 1(b)].

of pure silica microfiber. The measured linewidth of the lasing mode is about 0.04 nm, corresponding to a Q factor of about 10^4.

Figure 3 shows the dependence of spectrally integrated emission intensity on the pump energy. The pump energy is measured at the untapered input port. The lasing threshold estimated is about 0.13 μJ/pulse. A slope change and a good linearity of the pump-power dependent output are obviously observed when the pump energy exceeds the threshold.

It should be mentioned that more than one semiconductor nanowire can be integrated into the hybrid structure. Figure 4 shows the spectrally integrated emission intensity from a hybrid structure combining three ZnO nanowires and a 728-μm-diameter microfiber knot cavity [Fig. 1(b)]. The lasing threshold estimated is about 0.026 μJ/pulse. The lower threshold may be attributed to much sufficient pump absorption or the optimization of the knot configuration.

In conclusion, we have demonstrated a room temperature hybrid structure laser based on semiconductor nanowires and a silica microfiber knot cavity. The hybrid laser provides low threshold and narrow linewidth due to the combination of high gain of semiconductor nanowires and high Q factor of microfiber knots cavities. The hybrid structure, when integrated with other semiconductor nanowires, should allow similar operation from ultraviolet to near-infrared spectral range.

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