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An Evanescent Coupling Approach for Optical Characterization of ZnO Nanowires*

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Abstract: Using a nanoscale silica fiber taper, light can be efficiently coupled into a single ZnO nanowire by means of evanescent coupling. The method is valid for launching light into a single nanowire in the ultraviolet to infrared range with a coupling efficiency of 25%. Low-loss optical guiding of ZnO nanowires is demonstrated, and the photoluminescence of a single ZnO nanowire is also observed. Compared to conventional approaches in which a lens-focused laser beam is used to excite nanowires at specific wavelengths, this evanescent coupling approach has advantages such as high coupling efficiency and broad-band validity, and it is promising for the optical characterization of semiconductor nanowires or nanoribbons.

Key words: ZnO nanowire; evanescent coupling; optical characterization
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1 Introduction

With their low dimensions and high versatility, optical-quality semiconductor nanowires show great promise for use as nanoscale building blocks in photonic applications such as nanowire lasers, nanowire waveguides, and nanophotonic circuits[1~5]. Among such applicable optical nanowires, ZnO nanowire is of special interest because of its favorable properties, such as high uniformity for low optical loss, large bandgap for broadband optical transparency, efficient photoluminescence for active devices, large exciton binding energy, and high index for strong confinement of light. For photonic applications, the optical properties of nanowires (e.g. optical loss and photoluminescence) are critical to both the characterization and application of these nanowires, in which launching light into a single nanowire is an essential step. In previous works[3,6,7], a laser beam with wavelength in the absorption band of ZnO is focused by a lens to excite the nanowire to obtain luminescent emission. The photoluminescence, which is usually centered on certain wavelengths and is available within relatively narrow spectral bands, is used for optical characterization of the nanowire. With this technique, the usable light wavelength is limited to the available spectral range of the photoluminescence, and the coupling efficiency is relatively low. Here we introduce an evanescent coupling method for launching light into a single ZnO nanowire using a silica fiber nanotaper that is valid for launching light into a single nanowire in the ultraviolet to infrared range with a high coupling efficiency, and is promising for the optical characterization of semiconductor nanowires.

2 Synthesis of ZnO nanowires

The ZnO nanowires were synthesized with a carbothermal route[8]. The source materials were a mixture of commercial ZnO with a purity of 99.0% and graphite powder with a purity of 99.99% in a molar ratio of 1 : 1. The wires were grown on single crystalline silicon substrate without employing any catalyst or vacuum system. The furnace temperature was kept at 900 ℃ for 30～60min with a constant argon flow rate of 1600sccm. Long (> 50μm), straight ZnO nanowires were collected at the downstream end, where the temperature was a-

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bout 500 ℃. The as-grown nanowires were dispersed onto silicate substrates.

Scanning electronic microscope images of typical ZnO nanowires are shown in Fig. 1. The nanowires are grown along the [001] direction with diameters ranging from 250 to 600nm and lengths up to hundreds of micrometers (Fig. 1 (a)). The cross section of the nanowires is hexagonal (Fig. 1(b)). The high uniformity and defect-free surface of the nanowire are clear in Fig. 1(b), which give the wire high strength for micromanipulation.

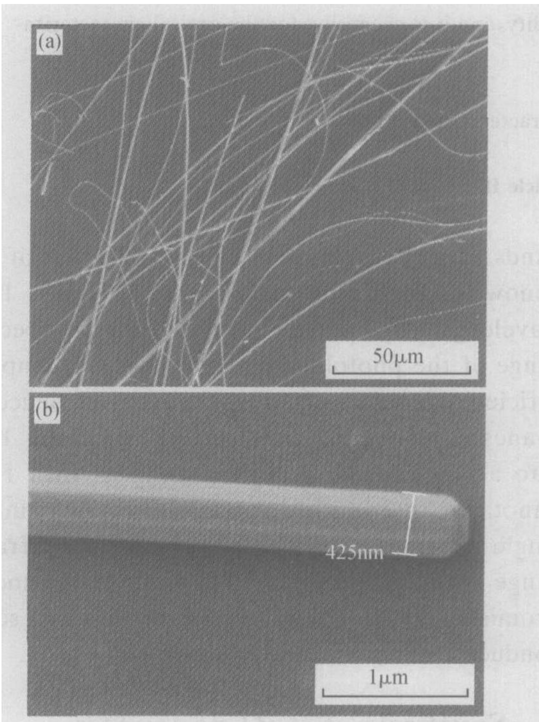

Fig. 1 SEM images of typical as-grown ZnO nanowires (a) Overhead view of ZnO nanowires; (b) Close-up of a 425nm-diameter

3 Optical launching of ZnO nanowires by evanescent coupling

The as-grown ZnO nanowires have favorable properties for optical wave guiding. For example, the high uniformity of the diameter and excellent smoothness of the sidewall of the wire make low-loss optical wave guiding possible; the large bandgap of ZnO (3.35eV) makes it transparent within a broad spectral range (down to 370nm on the short-wavelength end); and the high refractive index (about 2.0 at 633nm) makes it possible to tightly confine the guided field within small diameters.

For optical characterization, we launch light into a single nanowire using an evanescent coupling method, as illustrated in Fig. 2. In previous work, evanescently coupling light into a silica nanowire using an optical fiber tapered down to a uniform nanowire has been proven to be an efficient meth-

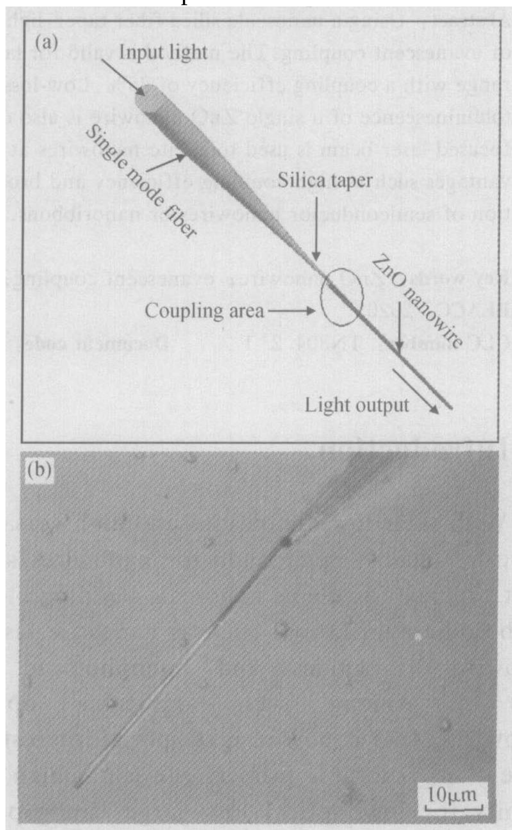

Fig. 2 Schematic diagram (a) and optical micrograph (b) of the evanescent coupling approach to launching light into a single nanowire

od[9,10]. However, the ZnO nanowires have a significantly different index from the silica nanotaper (1.46 at 633nm), resulting in large differences in propagation constants as shown in Fig. 3, which may make efficient coupling difficult. We use a nanotaper with a steep tapering shape to account for this difference. As shown in Fig. 2, a uniform ZnO nanowire is brought into contact with a nanotaper that tapers down from an optical fiber. Unlike the nanotapers used in previous works, this nanotaper maintains an obvious tapering tendency along its whole length, making it possible to match the effective index of the nanotaper to that of the

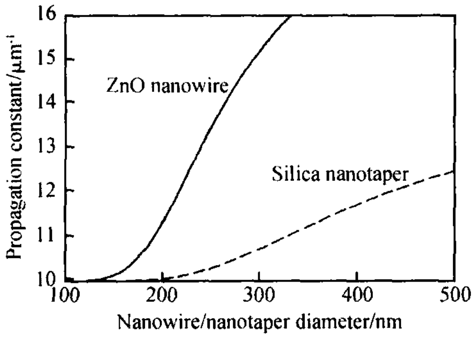

Fig. 3 Calculated propagation constants of a ZnO nanowire and a silica nanotaper at 633nm

nanowire within the coupling region. Using this scheme, effective coupling is obtained. Figure 4 shows an optical microscope image of coupling 633nm-wavelength light into a ZnO nanowire by means of a silica fiber nanotaper. The coupling efficiency, estimated by the ratio of the scattering intensities around the output end of the nanowire and the coupling area between the nanotaper and the nanowire, is about 25 %. This is much higher than that obtained using a lens-focused approach, in which a much lower fraction of the focused light can be accepted by the nanowire and the quantum efficiency of the photoluminescence is lower than the unit.

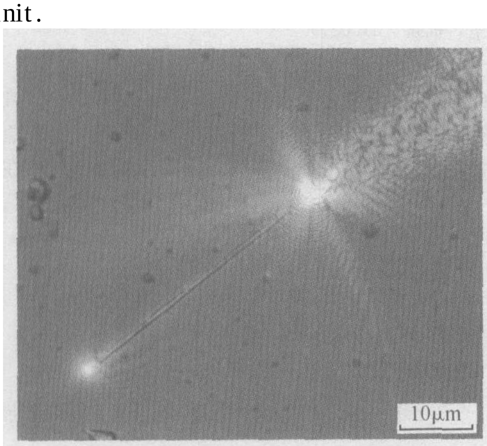

Fig. 4 Optical micrograph of launching 633nm light into a ZnO nanowire by means of a silica nanotaper

4 Optical characterization of ZnO nanowires

With the evanescent coupling technique, the optical properties of a single ZnO nanowire are investigated. Figure 5, for example, shows a 425nm-diameter ZnO nanowire guiding 633nm light on the surface of a silicate glass substrate. Because of the large index difference between the nanowires (2.01) and silicate substrate (1.52), the 633nm light is well confined on the surface of the glass and guided along the nanowires until it exits at the right end. No obvious scattering is observed along the whole length of the nanowire in spite of the strong guided intensity, indicating low optical loss in the wire.

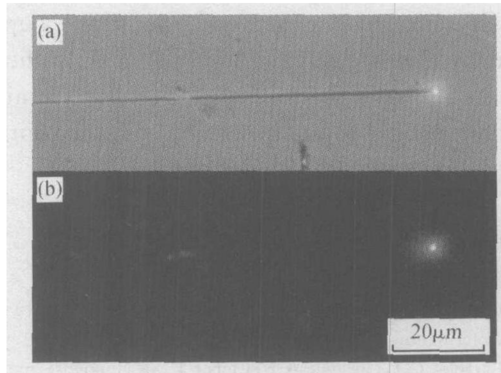

Fig. 5 Optical micrograph of a ZnO nanowire guiding 633nm light on the surface of a silicate glass substrate (a) With external illumination; (b) Without external illumination

Photoluminescence (PL) from a single ZnO nanowire is also observed when it is excited using an evanescent coupling method. Figure 6(a) shows optical microscope images of an 80μm-long ZnO nanowire before excitation. When the 325nm light (from a continuous wave He-Cd laser) is coupled into the nanowire by a silica nanotaper, obvious emission is observed at the end face of the nanowire, which can be used to measure the photoluminescence from a single wire.

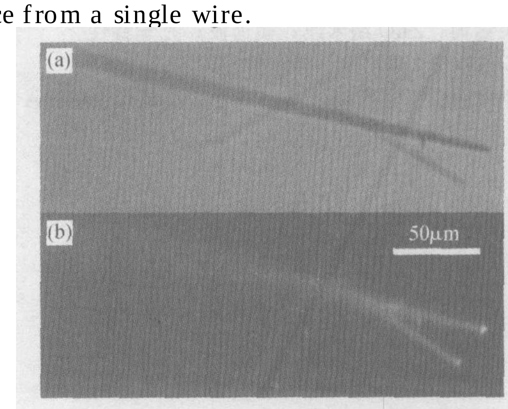

Fig. 6 Photoluminescence observed in a ZnO nanowire when it is excited at 325nm by means of evanescent coupling (a) Before excitation; (b) After excitation

5 Conclusion

In summary, an evanescent coupling approach

has been introduced for launching light into a single ZnO nanowire. A silica fiber nanotaper with a steep tapering shape is used for matching the effective indices of the nanowire and the nanotaper. A coupling efficiency of 25 % is obtained. With this coupling approach, low-loss optical guiding and photoluminescence of single ZnO nanowires are also observed. The high coupling efficiency and broad-band applicability of the evanescent coupling method make it very promising for the optical characterization of the optical-quality semiconductor nanowires.

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ZnO 纳米线光学特性测试的倏逝波耦合*

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摘要: 使用纳米氧化硅光纤探针,利用倏逝波耦合方法,将紫外到红外的激光成功地耦合进单根 ZnO 纳米线,耦合效率可达 25 %. 实验观测了单根纳米线的荧光特性,发现 ZnO 纳米线光传输损耗很低. 研究证明:采用透镜聚焦激发纳米线发光的传统耦合方法,只能使用特殊激发波长的光;而倏逝波耦合方法具有高效、适用性强的特点,在半导体纳米线和纳米带的光学特性研究中有广泛的应用前景.

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