ZnO subwavelength wires for fast-response mid-infrared detection

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Abstract: Room temperature operating thermal detection for mid-infrared light based on ZnO subwavelength wires has been demonstrated. Electric resistance in ZnO wires increases linearly with the intensity of incident light. Noise equivalent power (NEP) of 5.8 µW/Hz\(^{1/2}\) (at 1 kHz) with typical response times as fast as 1.3 ms is obtained at 10.6-µm wavelength. The sensitivity and response time of the detector are also found to be insensitive to the ambient.

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References and links

1. Introduction

Mid infrared (IR) detection, typically relying on thermal or photo response [1], has wide applications in the fields of medicine [2], remote sensing [3], environmental monitoring [4], and telecommunications [5]. Generally, IR photon detectors, including photoconductors, quantum well photodetectors, quantum dots photodetectors and superconductor detectors [1,6], offer advantages of fast response and high sensitivity, but usually require low-temperature operation with complex cooling equipments [3]. Thermal detectors, such as thermocouple detectors and resistance thermal detectors, provide the possibility for room-temperature operation with broadband response, but usually suffer from slow response times due to relatively large thermal inertia of the sensitive elements [1,3]. One way to speed up the response of a thermal detector is reducing the thermal inertia or equivalently the size of the sensitive element, through adopting air-bridge microstructure [7]. Recently, low-dimensional micro- or nanostructures have attracted extensive attentions in optical detection [8–10], among which zinc oxide (ZnO) micro- and nanowires show great commercial potential owing to their low cost and easy fabrication. So far most of the researches on ZnO nanowire detection are focused on UV photodetection [11–21]. Considering the relatively strong absorption in mid-IR regime (about 1 mm−1 from 8 to 30 μm) [22] and the excellent chemical and thermal stabilities of ZnO nanowire, here we propose mid-IR thermal detection based on ZnO subwavelength wires. In the work, we explore the photothermal response of ZnO subwavelength wires, and demonstrate a room-temperature-operation thermal detector with response time down to 1.3 ms at 10.6-μm wavelength.

2. Detector configuration

ZnO subwavelength wires were synthesized via a chemical vapor transport process [23]. Figure 1 shows a scanning electron microscope (SEM) image of a typical ZnO nanowire with 1.0-μm-diameter, smooth surface and hexagonal section. To assemble the detection structure, a ZnO wire, with diameter less than 3 μm, was first transferred to a grooved glass plate by micromanipulation. The wire was placed across two Ti/Au electrodes sputtered on the plate, as schematically illustrated in Fig. 2(a). To improve the electrical contact properties, a
A microdrop of In/Ga liquid alloy was used to cover the contact area to ensure an ohmic contact. The middle part of the wire was suspended above the groove (several hundred micrometers in width) to get isolation from the substrate. For reference, a typical as-fabricated detection structure, consisting of a 2.0-µm-diameter, 760-µm-length ZnO wire, is shown in Fig. 2(b).

![Fig. 1. The SEM image of a 1.0-µm-diameter ZnO wire.](image)

Light from a Coherent K-250 CO\textsubscript{2} laser, centered at the wavelength of 10.6 µm, was used to irradiate the ZnO wire. The laser beam was focused by a ZnSe lens (focus length = 5.0 cm) to a 220-µm-diameter spot on the ZnO wire. Since the dark resistance of the ZnO wire is very large, a constantly illumination from a halogen lamp (about 6800 lx) is applied on the ZnO wire for stable and reliable measurement of the response of the ZnO wire.

![Fig. 2. The schematic structure (a) and SEM image of a ZnO wire on a grooved glass plate (b).](image)

3. ZnO wire for mid-IR detection

When a ZnO wire absorbs mid-IR light, its temperature rises, leading to the change in the resistance that can be used to retrieve the intensity of the incident light. Figure 3 shows some typical $I$-$V$ characteristics of a 2.9-µm-diameter, 520-µm-length ZnO wire under irradiation of 10.6-µm-wavelength light at various intensities, for reference, the $I$-$V$ curve of the ZnO wire without IR irradiation is provided. The linear shape of the curves in the range of $-10$ to $10$ V reveals good ohmic contacts. The current decreases with the increase of irradiation power: as the light intensity increases to 22.8 mW, the current reduces by 38%. Supposing only the 226-µm-length irradiated part of ZnO wire elevating temperature, the resistance of this part increases by 144%.
Figure 3. *I-V* characteristics of a 2.9-μm-diameter, 520-μm-length ZnO wire as a function of 10.6-μm-wavelength light intensity.

Figure 4 shows the irradiation-intensity-dependent resistance of a 2.0-μm-diameter, 760-μm-length ZnO wire. As can be seen, the resistance increases linearly with intensity of the irradiation. The inset image in Fig. 4 shows the repetition-frequency dependence of the resistance change of the ZnO wire to the incident pulses (500 pJ/pulse, 25 µs pulse width). The amplitude of the resistance changes decreases with the increasing repetition frequency. By means of frequency domain analysis [24], we obtain the noise intensity of 700 µV/Hz^{1/2} (at 1kHz), which corresponds to a noise equivalent power (NEP) of 5.8 µW/Hz^{1/2}.

Recent study shows that the response of ZnO nanowire for UV photodetection is significantly influenced by ambient [17]. To investigate the influence of ambient on ZnO wire for mid-IR detection, we measured resistance of a 2.0-μm-diameter, 760-μm-length ZnO wire (the same ZnO wire shown Fig. 4) in typical ambient gases including air, argon, nitrogen, and oxygen, with results shown in Fig. 5. The 10.6-μm-wavelength light was irradiated on the wire with a pulse period of 9 ms and a pulse width of 0.9 ms. Though the background resistance varies in different atmospheres, the amplitude and response time are insensitive to the ambient gases. The estimated response time of the ZnO wire mid-IR detection is about 1.3 ms when the resistance of ZnO wire falls from 37.2 to 34.5 MΩ in the air, which is much faster than other types of room-temperature-operated microbolometers or thermocouples [9,25–31], and three orders of magnitude faster than that in ZnO nanowire UV photodetectors [11,14,21].
In UV and mid-IR spectral ranges, ZnO wires have different response mechanisms. When mid-IR photon is absorbed by ZnO wires, the photon energy is converted to the thermal energy, heating up the ZnO wire. When temperature rises, thermal lattice vibration becomes stronger, leading to stronger scattering of carriers in ZnO wire, which is in turn, reduces the mean free paths of carriers, resulting in the increasing of the resistance. On the other hand, the temperature rising may excite electrons to the conduction band and increase the density of carriers, resulting in the decreasing of the resistance. However, at room temperature and above, with the halogen lamp illumination, electrons on the shallow doping levels have already been excited, and the free-carrier density is almost saturated. Therefore, heating of the ZnO wires would not increase the density of carriers obviously, and the resistance of the ZnO wire would increase when it is irradiated by mid-IR light.

As a kind of thermal detection, the response time of the ZnO wire detection can be theoretically estimated using the time constant \( \tau \)
\[
\tau = \frac{H}{G},
\]
in which the heat capacity (of the irradiated part of ZnO wire) \( H \) is about \( 5.5 \times 10^{-9} \) J/K, and the thermal conductivity \( G \) is about \( 5.0 \times 10^{-6} \) W/K [32,33]. Calculated \( \tau \) is about 1.1 ms, which coincides well with the measured value of 1.3 ms.

4. Conclusion

In conclusion, we demonstrate fast thermal detection of mid-IR light based on ZnO wires. A NEP of 5.8 \( \mu \)W/Hz\(^{1/2} \) (at 1kHz) and a typical response time of 1.3 ms are obtained at 10.6-\( \mu \)m wavelength. The sensitivity and response time of the detector are found to be insensitive to the ambient. The low thermal inertia of ZnO wire allows the response time down to the order of millisecond. Although the light used in this work is a monochromatic 10.6-\( \mu \)m-wavelength laser, the fast and sensitive response of the ZnO wire can be extended to a wider mid-IR spectrum owning to the broadband absorption of ZnO in the mid-IR spectral range, and will be promising for fast-response mid-infrared detection.

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