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Narrow linewidth carbon nanotube blackbody emitter with a microcavity

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1. Introduction

Carbon nanotubes (CNTs) are ideal one-dimensional materials with interesting electrical, optical and thermal properties. Electroluminescence from an individual CNT has been attracted as nano light source for optical circuit and on-chip interconnect because the devices are directly fabricated on Si substrate. Furthermore, CNT film light emitter with high intensity and high yield fabrication is good for applications. CNT film emission induced by current injection is mainly originated from two (types of) mechanisms: the recombination of electrons and holes excited by carrier injection and blackbody radiation associated with Joule heating [1,2]. Whereas the wafer-scale fabrication of the electroluminescence device is not easy because of the preparation difficulty of the uniform semiconductor CNT films, the blackbody emitter is easy to be fabricated because the blackbody radiation can be obtained from the mixture of semiconducting and metallic CNTs. However, in the optical communication, the broad spectrum of the blackbody radiation limits the communication bandwidth by wavelength dispersion. In this study, we fabricated blackbody radiation emitter with Fabry-Perot microcavity structure, which consists of two types of mirrors, gold mirrors [4] and distributed Bragg reflectors (DBR) [3]. We observed narrow band emission from the fabricated emitters. The obtained experimental emission spectrum is modeled that the product of the original blackbody radiation of CNT film and the output ratio from inside of the microcavity. In particular, we also found out applied voltage dependence of the peak shifts and the FWHM by comparison of experimental and theoretical emission spectra.

2. Experimental procedure

Figure 1 shows the device structures of gold mirror and DBR devices. CNT film pattern was fabricated by electron beam lithography (EB). CNT film was fabricated by two kinds of methods which were chemical vapor deposition (CVD) and CNTs dispersion. The electrode was fabricated by EB and electron beam deposition (EBD). Gold mirror cavity consisted of three dielectric layers; 212 nm SiO_2 fabricated by sputtering, 10 nm Al_2O_3 deposited by atomic layer deposition (ALD), 220 nm SiO_2 sandwiched between a top of gold mirror (50 nm) and a parallel bottom gold mirror (75 nm). DBR consisted of 120 nm TiO_2 layers and 224 nm SiO_2 layers fabricated by sputtering.

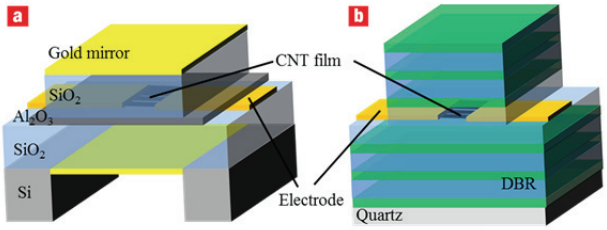

Fig. 1. 3D schematic pictures of the CNT film light emitter with microcavity: (a) Au metal mirror device and (b) distributed Bragg reflector device.

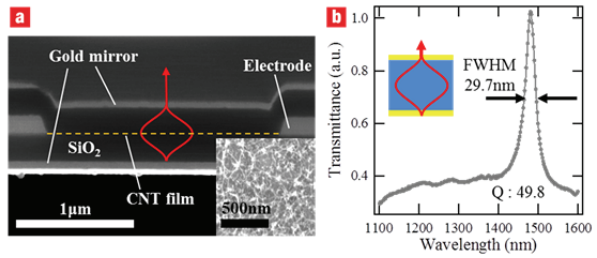

Fig. 2. (a) Cross section SEM image of gold mirror microcavity device. Inset: SEM image of CNT film. (b) Transmittance of the microcavity device. Inset: Schematic photonic mode profile.

3. Results

CNT film light emitter with gold mirror microcavity

We fabricated CNT film light emitter with gold mirror microcavity. The cross section SEM image of the device is shown in Fig.2a. We measured the transmittance of microcavity. The transmittance is shown in Fig.2b. The spectrum exhibits a sharp peak (the on-axis resonance) with the peak wavelength λ of 1479.9 nm, the full-width at half-maximum (FWHM) $\Delta\lambda$ of 29.7 nm and the quality factor (Q-factor = $\lambda/\Delta\lambda$) of 49.8.

Using this gold mirror microcavity device, the electroluminescence were measured under applying V_{ds} (= 4, 6, 8, 10V) using low numerical aperture (NA) objective lens (NA: 0.10) (Figure 3a). Very sharp emission with the FWHM of 49.3 nm and Q-factor of 30.2 was observed at 10 V. To understand the obtained emission spectra with a very sharp peak, we simulated the emission spectra. The simulated spectra (Figure 3b) are in very good agreement with experimental data. The temperature of the heated CNT in a CNT film at each V_{ds} is estimated from these fitting. From the T-V_{ds} characteristic, the temperature has a linear dependence to V_{ds}, which is the same behavior as the bare

blackbody radiation from CNT film without microcavity. Peak wavelength and FWHM extracted from experiment and simulation are shown in Figure 3c. These simulated behaviors, in which peak wavelength is slightly blue-shifted with increasing applied voltage and FWHM is almost constant, are consistent with the experimental results. The blue shift of the emission peak at high V_{ds} is caused by the decrease of the slope in the bare blackbody radiation spectra with increasing CNT temperature (Figure 3f). At low temperature, the peak wavelength of the emission from the cavity is longer than that of the cavity transmittance because the emission spectrum is inclined. On the other hand, at high temperature, the peak wavelength of emission nearly corresponds to that of the cavity transmittance because the slope of the bare emission spectrum is mostly flat. In contrast, the FWHM of the emission shown in Figure 3e is independent of V_{ds} because the emission spectra are symmetric and the wavelengths at half-maximum are almost uniformly shifted with increasing temperature.

CNT film light emitter with DBR

We fabricated CNT film light emitter with DBR. The cross section SEM image is shown in Fig.4a and the transmittance is shown in Fig.4b and c. From the transmittance, photonic band gap (PBG) is observed between about 1000 nm and 1500 nm. The peak wavelength, FWHM and Q-factor of the DBR transmittance are 1233.4 nm, 6.5 nm and 189.0 respectively.

The measured emission spectra collected by objective lens with NA of 0.55 are shown in Fig.5a. The peak wavelength and FWHM of obtained spectra at 13 V are 1179.2 nm and 46.2 nm respectively.

The observed emission spectra (Fig.5a) have three emissions at 'a', 'b' and 'resonant'. The emission at 'resonant' is caused by resonant peak of DBR. FWHM of the resonant peak from DBR device, ~46 nm is lower than that from gold mirror microcavity device collected by the same objective lens, ~70 nm. The emissions at 'a' and 'b' are originated by PBG edges of top DBR. Therefore, we can obtain the temperature of CNT film from intensity ratio at 'a' and 'b' by using Plank blackbody radiation equation. The obtained temperatures are shown in Fig.5b. From the obtained temperatures, we also show original blackbody radiation at 13 V in Fig.5a (black line).

4. Conclusions

We obtained the sharp blackbody radiation from CNT film light emitter with gold mirror microcavity and DBR. The devices realize nano light emitter with high speed modulation at desired peak position. Such nano light emitting devices have the future of optical communication and on-chip optical interconnect.

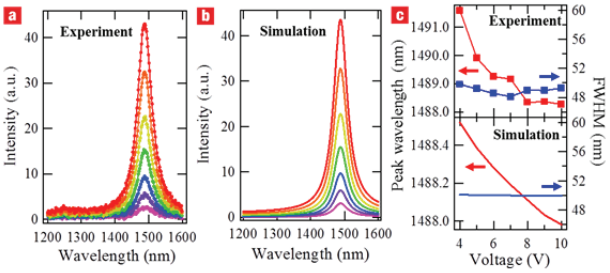

Fig.3. (a) Emission spectra from film CNT light emitter with gold mirror microcavity at seven biases V= 10 V (red), 9 V (orange), 8 V (yellow),7 V (green), 6 V (blue), 5 V (purple), 4 V (magenta). (b) Simulated emission spectra. (c) Peak wavelength and FWHM extracted from experimental and simulated emission spectra.

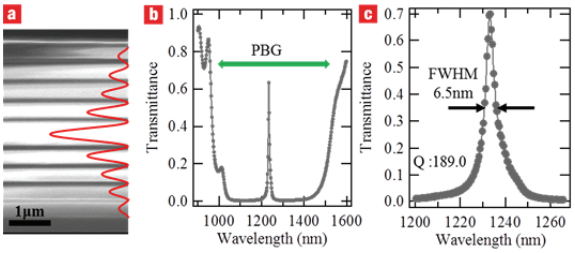

Fig.4. (a) Cross section SEM image of DBR device. (b) Transmittance of fabricated DBR. (c) Magnified resonant peak of transmittance.

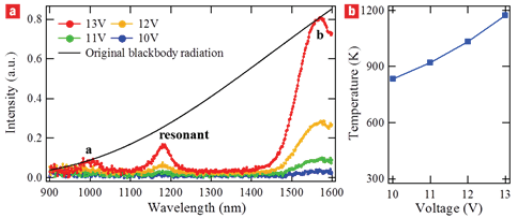

Fig.5. (a) Emission spectra from DBR device at 13 V (red), 12 V (yellow), 11 V (green), 10 V (blue). (Black line) Original blackbody radiation at 13 V = 1172.6 K. (b) CNT film temperature versus applied voltage.

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