ELECTRICAL CONDUCTIVITY AND EMISSION PROPERTIES OF CARBON NANOTUBES

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Electrical conductivity and photon emission, as well as electron emission from carbon nanotubes, have been studied under the passage of current through them before and after their dispersion. It has been shown that the dispersion changes properties of C-nanotubes and causes the appearance of electron and photon emissions in the voltage region, where the conduction current-voltage characteristic becomes superlinear. There is a maximum in the photon emission spectrum ($\lambda \approx$580 nm), which differs from the Planck black-body radiation spectrum registered for the initial C-nanotubes. The model of hot electrons has been proposed to explain the mechanism of electron and photon emissions.

1. Introduction

Nowadays, carbon nanotubes are actively investigated for the use in nanoscale applications because of their unique electron properties. For example, their electrical conductivity is very sensitive to the tube diameter and the wrapping angle (helicity of an arrangement of graphitic rings in the walls). Thus, even a small change in these parameters results in a shift from the metallic to the semiconducting state [1].

Use of the carbon nanotubes as field emitters for flat panel displays is promising. In this case, the display size can be changed within a wide range (from less than 1 mm^2 up to hundreds of cm^2) [2].

The luminescent properties of C-nanotubes enable the light sources of new types to be created. They can be a base for the elaboration of integrated nanoscale optoelectronic and photon devices [3–5].

Recently a number of works devoted to the study of the photon emission from C-nanotubes observed under the current passage through them have been published [6–8]. A nanotube bunch overlapping a narrow gap between contacts was usually used in these experiments. In some works, a separate nanotube was under investigation, and the tip of a scanning tunneling microscope (STM) served as a contact [9].

Till now, there is no full clearness concerning the mechanism of photon emission from carbon nanotubes. The photon emission in the near IR range was described in works [10,11] and was interpreted as the interband photoluminescence. In work [12], the photon emission in the IR range was attributed to the emitting recombination of an electron-hole pair. The photon emission in separate multiwall carbon nanotubes adsorbed on a high-orientation pyrolytic graphite surface was excited with the STM tunnel current [9]. The authors ascribed this emission to the emitting electron transitions between singularities of the one-dimensional energy bands of multiwall nanotubes. In other works, the photon emission was explained by Planck's black-body radiation under the current passage [7, 8].

A study of the spectra of photon emission observed in the visible spectrum and the near IR range from a single multiwall C-nanotube was performed in work [7]. It has been shown that an increase of a voltage applied to the nanotube results in a stepped decrease of the conduction current corresponding to the sequential destruction of individual shells. This occurs because of the excess conduction current that induces heat due to the electron-lattice interaction and sublimation. The measured optical emission spectra show that there is a peak at $\approx$550 nm against the background of the Planck black-body radiation. The origin of this optical emission is not yet clear and calls for the further investigation. From our point of view, it is just the fact that the dispersion of some carbon shells is possible under a critical current increase resulting in the formation of C-islands may lead to the appearance of new peculiarities in the photon emission spectra.

The point is that our previous investigations of electrophysical properties of another nanoscale objects such as metal nanometer islands on a dielectric

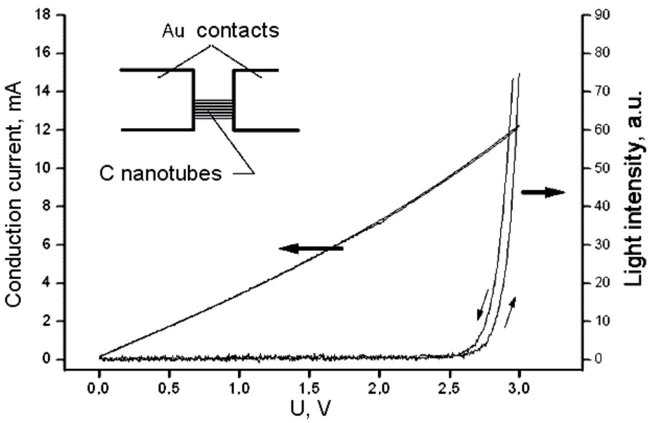

Fig. 1. Conduction current-voltage characteristic of a bunch of initial C-nanotubes and the photon emission intensity as a function of the applied voltage. Inset: the schematic of an experimental sample

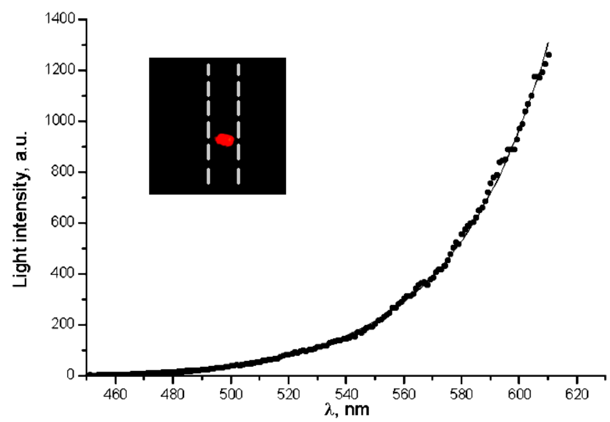

Fig. 2. Photon emission spectrum recorded at the voltage $U = 3$ V. Inset: the image of the luminescence (hatched area) of a bunch of initial C-nanotubes between metal film contacts shown by a dashed line

substrate have been shown that the photon emission is also observed in them under the current passage, and spectral bands are in the visible spectrum [13]. A special feature of these objects is the ability to generate the so-called “hot” nonequilibrium electrons in the stationary regime that causes the electron and photon emissions. That is the reason why the study of electrical conductivity and emission properties of C-nanotubes both in the initial form and after their dispersion into nanoscale islands is of particular interest.

Thus, the aim of our work is to research the emission properties of C-nanotubes when they are energized by the passage of a current through them. The nanotubes were studied before, as well as after the dispersion of the same object. The procedure developed for the investigation of the electron and photon emissions from metal nano-island films [13] is used in the present work.

2. Experimental Technique

Experimental samples for the study of C-nanotubes were planar cells of the gap type. They were prepared according the following technology. At first, gold film electrodes separated with a gap 30 mkm in width were deposited on a dielectric substrate (quartz, glass) by the thermal vacuum evaporation. Then a bunch of C-nanotubes was placed onto the gap overlapping it. A schematic is given in Fig. 1, inset. The prepared sample was installed into a special glass device with a flat window, through which the photon emission spectra were registered. The device was evacuated down to 10^{-7} Torr, and all experiments were performed under such vacuum conditions.

The electric current passed through the sample, which caused the appearance of the photon emission. The luminescent spectra were recorded with a monochromator (LOMO MDR-23) and photodetectors.

The structure of C-nanotubes was studied with the help of a scanning tunneling microscope (NT MDT) before and after their dispersion.

3. Experimental Results and Discussion

The conduction current-voltage characteristics of the bunch of initial C-nanotubes situated between the Au film electrodes were measured in the voltage range U≤3 V. A typical characteristic given in Fig. 1 is linear. The luminescence intensity as a function of the applied voltage is shown as well.

Figure 2 presents the luminescence spectrum which is a monitonically increasing stepless curve which is obviously the short-wave section of the Planck black-body radiation spectrum. The similar spectra were previously observed in work [7].

Figure 3,*a* shows the STM image of the initial bunch of C-nanotubes.

A gradual increase of the applied voltage results in the destruction of the nanotube bunch, i.e. C-nanotubes are dispersed in separate fragments and nanoparticles coupled by tunneling and fill the gap between the contacts. Figure 3,*b* gives the STM image of dispersed nanotubes. Such a dispersion causes a change of the electrical conductivity characteristics, as well as the

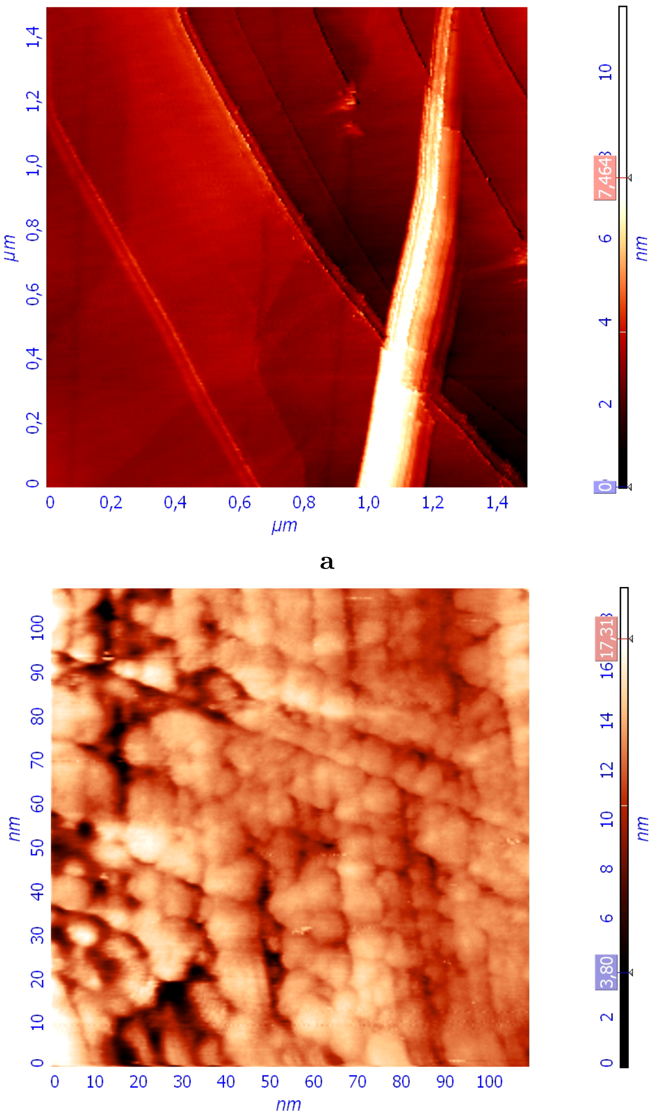

Fig. 3. STM image of C-nanotubes before (*a*) and after (*b*) their dispersion

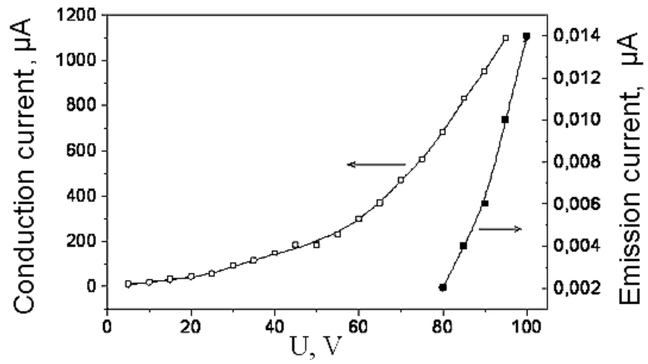

Fig. 4. Current-voltage characteristic of conduction and emission currents from dispersed C-nanotubes

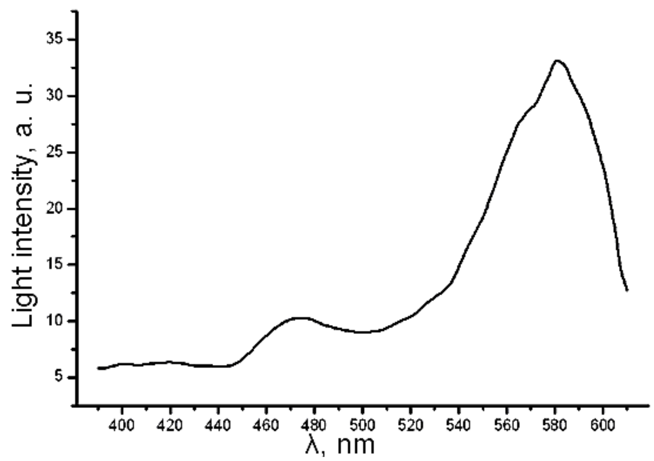

Fig. 5. Spectrum of photon emission from dispersed C-nanotubes

appearance of the emission properties differing from ones observed before the dispersion.

In particular, the shape of the conduction current-voltage characteristic is substantially changed. It modifies from the linear to superlinear type starting from ≈ 25 V (Fig. 4, light squares), and the electron and photon emissions are observed beginning from ≈ 70 V. The current-voltage characteristic of the electron emission current is also shown in Fig. 4 (black squares), and the photon emission spectrum is given in Fig. 5. It is seen that the spectral characteristic is not monotone: a maximum in the visible spectrum at ≈ 580 nm appears. This is typical of the nonequilibrium mechanism of the light emission caused by hot electrons [13].

The similarity of the electrophysical characteristics of dispersed C-nanotubes to characteristics measured for the nano-island metal films [13] being an ensemble of nanometer islands coupled by tunneling, namely, a deviation of the conduction current-voltage curves from linearity, the appearance of the electron and photon emissions in this region, and the distinction between the light emission spectra and the black-body radiation spectra, gives ground to suppose that mechanisms of these phenomena are similar.

As known from the literature [13], the island metal films, as distinct from bulk metals and similar to semiconductors are systems, in which the so-called "hot" (nonequilibrium) electrons can be generated in a stationary regime. It can occur under feeding a power into nano-islands with the help of the current passage through them or due to the excitation by laser radiation.

In both cases, the energy is absorbed by the electron gas in individual islands which is heated up to a temperature vastly larger than the lattice temperature due to the strong weakening (by orders of magnitudes) of the electron-lattice energy exchange in metal nanoparticles, whose size is smaller than the electron mean free path. It is just the generation of hot electrons that leads to the occurrence of the electron and photon emissions. The latter phenomenon can be caused by the inverse surface photoeffect [14].

4. Conclusions

1. It has been shown that the photon emission with the Planck black-body radiation spectrum is observed from C-nanotubes at the passage of an electric current through them.
2. Dispersion changes the C-nanotubes properties; it causes the appearance of the electron and photon emissions in the voltage region, where the conduction current-voltage characteristic becomes superlinear. The photon emission spectrum is different from the Planck black-body radiation one.
3. The model of "hot" electrons working out for the island metal films was proposed to explain the mechanism of electron and photon emissions from C-nanotubes, which does not contradict the obtained experimental results.

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ЕЛЕКТРОПРОВІДНІСТЬ І ЕМІСІЙНІ ВЛАСТИВОСТІ ВУГЛЕЦЕВИХ НАНОТРУБОК

Л. Відута, О. Кияєв, А. Марченко, В. Нечитайло, Р. Федорович, В. Чорний, А. Вітухновський, В. Черепанов, Д. Чубич

Р е з ю м е

Досліджено електропровідність і світіння, а також електронну емісію з вуглецевих нанотрубок при протіканні через них струму до і після їх диспергування. Показано, що диспергування змінює властивості С-нанотрубок і приводить до появи електронної та фотонної емісії в області напруг, де вольтамперна характеристика струму провідності стає надлінійною. Спектр світіння має максимум у видимій області спектра ($\lambda \approx$580 нм) і є відмінним від планківського спектра випромінювання чорного тіла, який реєструється для висхідних нанотрубок. Для пояснення механізму електронної і фотонної емісії запропоновано модель гарячих електронів.