Emission Properties of Selectively Grown Carbon Nanotubes

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Abstract

Field-emission (FE) characteristics of different photolithographically patterned carbon nanotubes (CNTs) films have been studied. The total FE current is the highest value [2.8 mA (~106 mA/cm^2) at 7.5 V/μm] in patterned CNTs film with the window size of 60 μm × 60 μm and the spacing of 120 μm. It was found that the total widow area is more important factor for the total FE current than the total window length. The contact resistance between CNTs and substrate would be a crucial factor for detachment of CNTs from the substrate.

1. Introduction

Since the first discovery of carbon nanotubes (CNTs) in 1991, there have been plenty of intensive studies on field emission (FE) of CNTs because of their superior mechanical strength, extreme aspect ratios, large local field enhancement [1] and thus yield considerable FE currents at relatively low applied voltages. In order to increase in FE current from CNTs films, a number of researches on selective growth of CNTs have been also carried out using various methods such as photolithography [2], electron-beam lithography [3], ion beam surface modification [4], pulse-current electrochemical deposition of catalyst particles [5], and plasma etching on catalyst layer [6]. To our knowledge, however, there has been no report on relationships between morphological parameters in designed pattern and FE characteristics. In this work, we report a study on such relationships using photolithography technology.

2. Experiments

We have directly grown CNTs on the Ni substrates by direct-current plasma-enhanced chemical-vapor deposition using a gas mixture of C_2H_2 and NH_3 at relatively low temperature (650 °C). In this study, we report a relationship between the field emission (FE) properties of patterned CNTs film and the pattern morphologies such as the total window length and area. FE characteristic of CNTs was evaluated in a vacuum of 10^{-6} Torr in a parallel diode configuration.

3. Results and Discussion

In order to investigate the effect of pattern sizes and spacing between them on FE characteristics of CNTs, three kinds of patterns, such as the window size of 60 μm × 60 μm and the spacing of 120 μm, the window size of 60 μm × 60 μm and the spacing of 240 μm, and the window size of 120 μm × 120 μm and the spacing of 240 μm, respectively, were used as shown in Fig. 1, which was taken after FE measurements. It can be seen that plenty of CNTs were locally detached from the substrate after FE measurement. This may be due to the contact series resistance between CNTs and the substrate, i.e. if the contact resistance is larger than the bulk resistance of CNTs, the CNTs with large contact resistance is easily detached from the substrate as the applied voltage increased during FE.

Figure 2(a) and 2(b) show the current–voltage (I–V) characteristics and its Fowler–Nordheim (FN) fittings of different patterned CNTs films, respectively. The turn-on field is defined as the electric field where the emission current occurs in FN plot. The turn-on field has the lowest value of 1.9 V/μm in the sample with the window size of 120 μm × 120 μm and the spacing of 240 μm. Based on the FN fitting, we can estimate β. The FN model (with image-charge correction) states that the current I [A] per emitter may vary with the local field at the emitter surface F [V/m] as [7],

$$I = f_{FN}(V) \quad (1)$$

$$I = A\frac{1.5\times10^{-6}}{\phi}\left(\frac{V}{d}\right)^2 \beta^2 \exp\left(\frac{10.4}{\sqrt{\phi}}\right)\exp\left(\frac{-6.44\times10^9\phi^{1.5}d}{\beta V}\right) \quad (2)$$

where A has the dimension of an area [m^2] and represents, in a first approximation, the emitting area. The work function ϕ is in eV. The field enhancement factor β is defined as $F=\beta V/d$, where

V is the applied voltage and d is the interelectrode distance. β can be calculated from the slope of the FN plot [$\ln(I/V^2)$ vs. $1/V$], if the work function of the emitter is given (assuming 5 eV in this article). From the FN fitting, it is found that β of the sample with the window size of 120 μm × 120 μm and the spacing of 240 μm is 1269. Corresponding β and turn-on field of each sample are shown in Fig. 3(a).

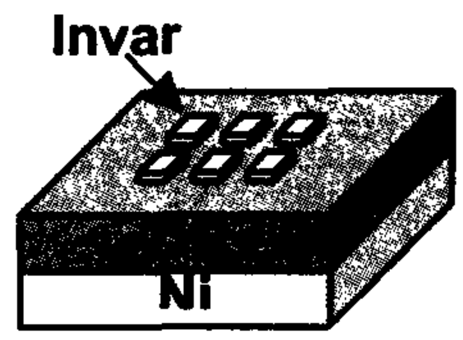
As shown in Fig. 3(a), while the turn-on fields of two samples—the samples having the identical window size of 60 μm × 60 μm but different spacing 120 μm and 240 μm—are nearly the same of 2.8 V/μm, the value of β from the sample with the spacing of 240 μm is somewhat larger. This is due to the fact that although two samples have the identical window size (60 μm × 60 μm), the field screening effect on the sample with the spacing of 240 μm is more reduced than that with the spacing of 120 μm. It is conjectured that the reason why the β of the sample with the window size of 120 μm × 120 μm and the spacing of 240 μm has the best value of 1269 is the fact that the more the window size increase, the smaller the electric field concentration effect on patterned CNTs film is during the growth stage of CNTs. This results in a decrease in the growth rate of CNTs and the field screening effect at a given spacing between adjacent windows. As shown in Fig. 3(b), the total FE current [2.8 mA (~106 mA/cm^2) at 7.5 V/μm] of the sample with the window size of 60 μm × 60 μm and the spacing of 120 μm is slightly larger than that [2.6 mA (~92 mA/cm^2) at 5.7 V/μm] with the window size of 120 μm × 120 μm and the spacing of 240 μm. It is likely that although the β of the latter is larger, the series resistance (e.g. contact resistance) between CNTs and the substrate of the latter is larger that that of the former, leading to saturation of FE current at higher voltages and/or detachment of CNTs from the substrate. Such the detachment phenomena of CNTs can be also seen in Fig. 1(c), compared in Fig 1(b). Another interesting fact is that the total FE current of the sample with the window size of 60 μm × 60 μm and spacing of 240 μm has the lowest value [1.6 mA, Fig. 3(b)] even though it has a medium value of the β [~1094, Fig. 3(a)]. It is attributed to the fact that while the β of the sample with the spacing of 240 μm is somewhat larger than the sample with the spacing of 120 μm at the same window size of 60 μm × 60 μm due to the decrease in field screening effect, the effective emission sites of CNTs film in the former decreased per unit area, resulting in the decrease in the total FE current.

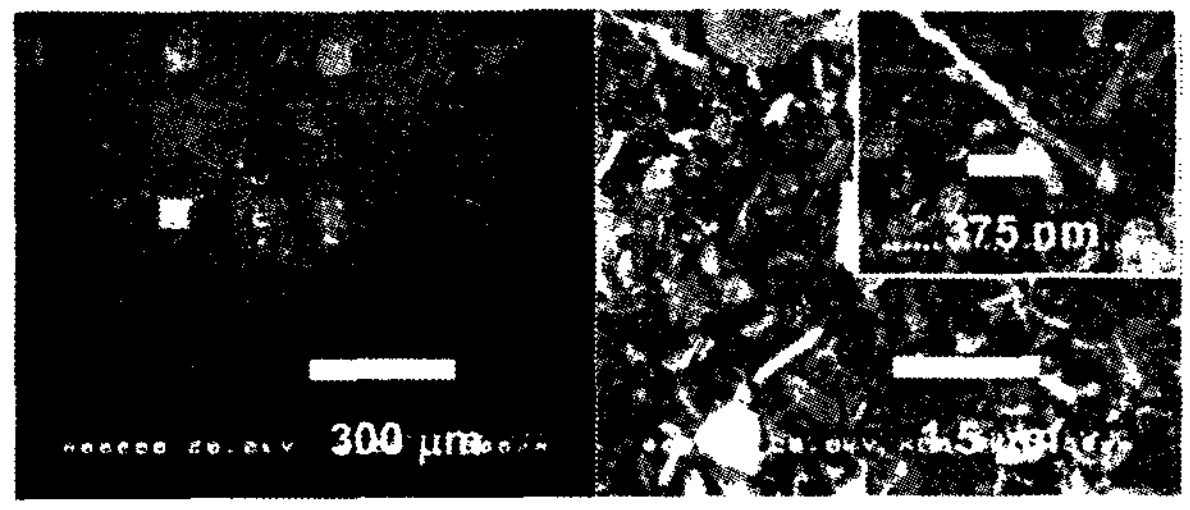
In order to study the main factor that affect the total FE current of CNTs film, the total window edge length and area are calculated and shown in Fig 4(a) and 4(b), respectively. Among those the plot pattern of the latter is quite similar to that of the total FE current [shown in Fig. (b)]. Therefore it seem that the total widow area is more important factor for the total FE current than the total window length.

4. Conclusion

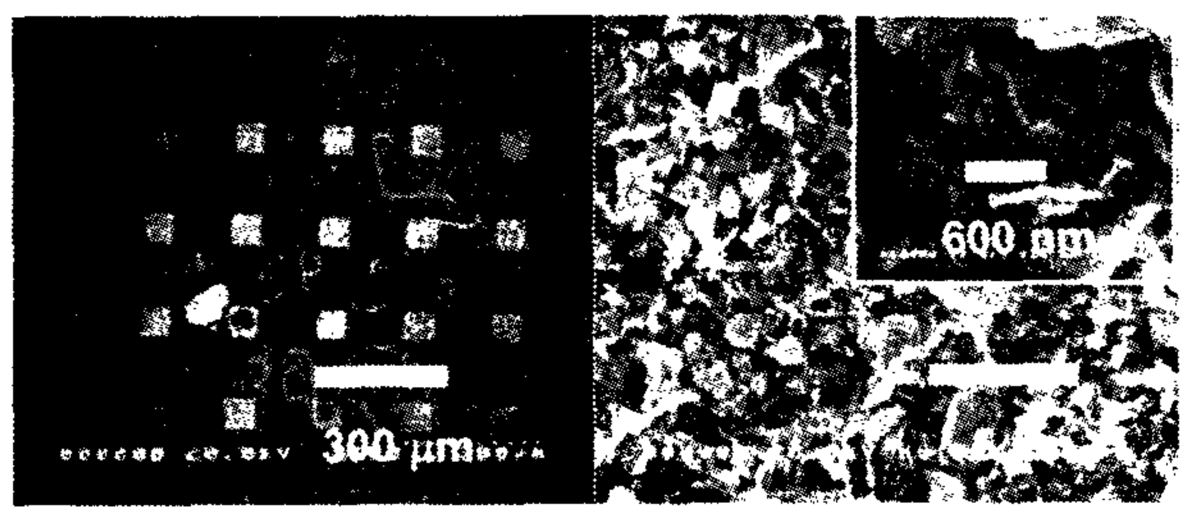
We studied FE characteristics of different photolithographically patterned CNTs films. The total FE current is the highest value [2.8 mA (~106 mA/cm^2) at 7.5 V/μm] in patterned CNTs film with the window size of 60 μm × 60 μm and the spacing of 120 μm. It was found that the total widow area is more important factor for the total FE current than the total window length. The contact resistance between CNTs and substrate would be a crucial factor for detachment of CNTs from the substrate.

5. Figures/Captions

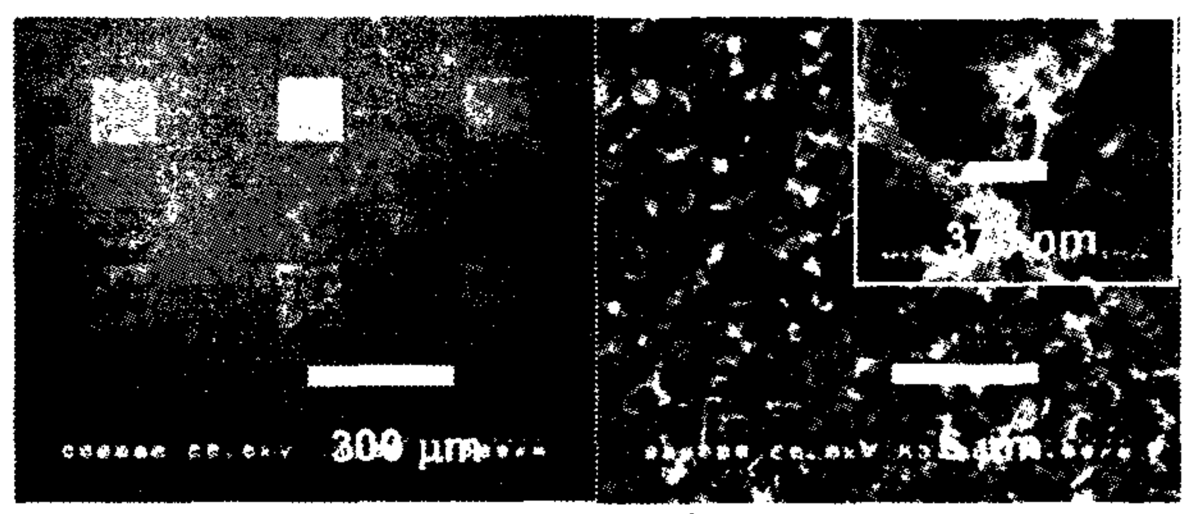




(a) [60 μm×60 μm, Spacing 240 μm]



(b) [60 μm×60 μm, Spacing 120 μm]



(c) [120 μm×120 μm, Spacing 240 μm]

Fig. 1. SEM images of variously patterned grown CNTs films with (a) the window size of 60 μm × 60 μm and spacing of 240 μm, (b) the window size of 60 μm × 60 μm and spacing of 120 μm, and (c) the window size of 120 μm × 120 μm and spacing of 240 μm, respectively.

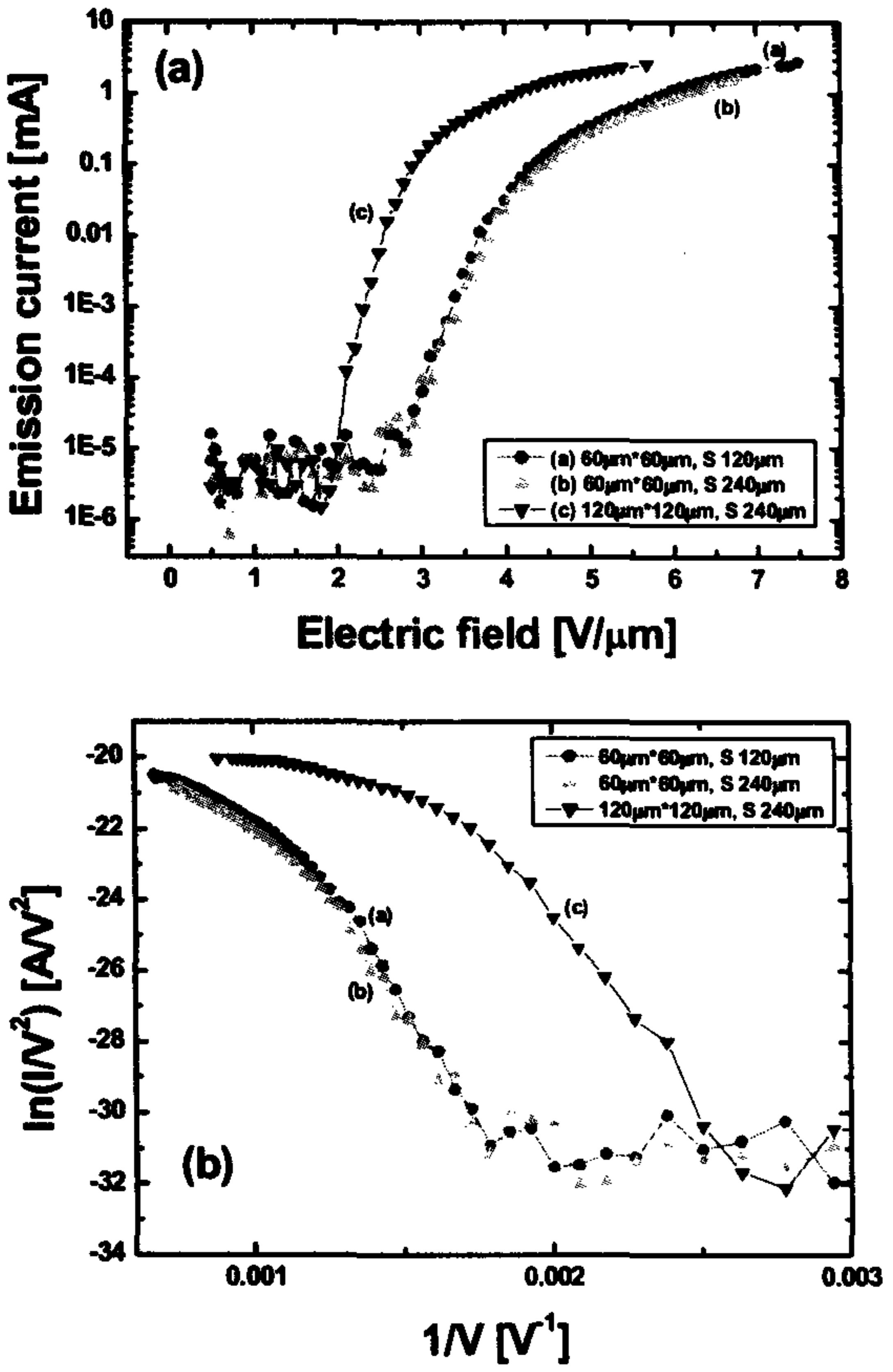


Fig. 2. Current–voltage *(I–V)* of differently patterned CNTs films on TiN/Ni substrate using Invar catalyst (a) and FN plot (b).

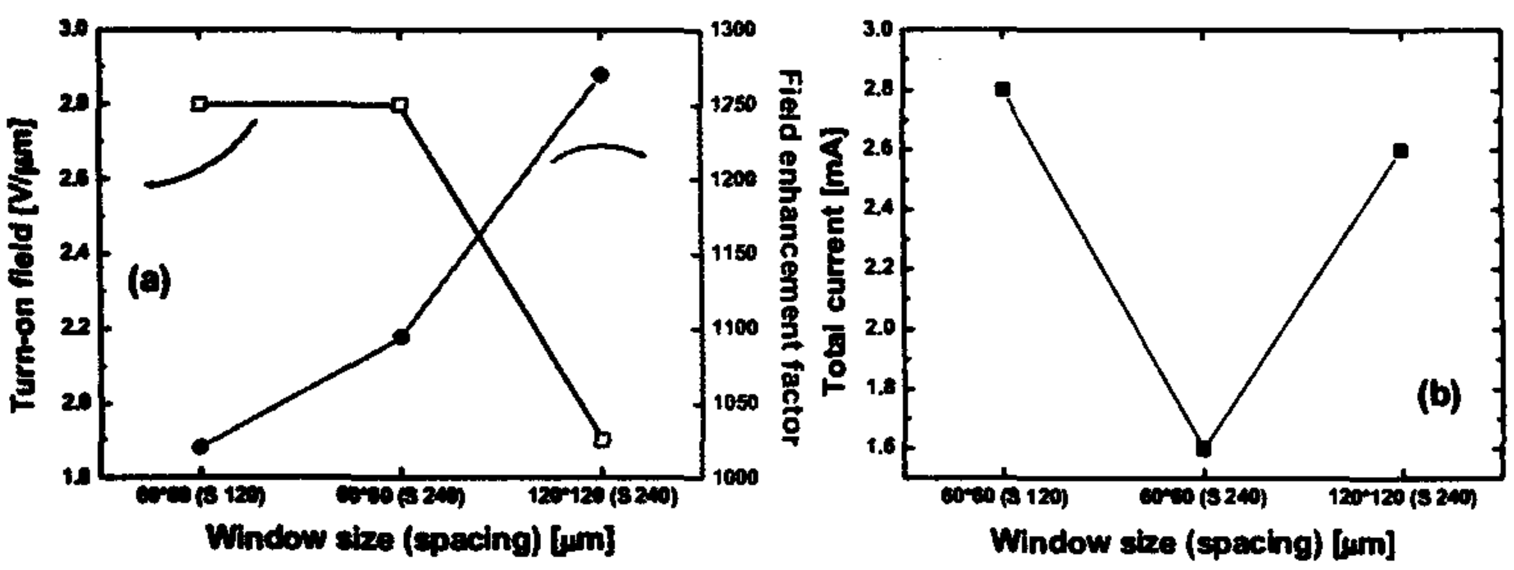


Fig. 3. Plots showing FE chacateristics of (a) turn-on field and field enhancement factor (β), and (b) total field-emission current.

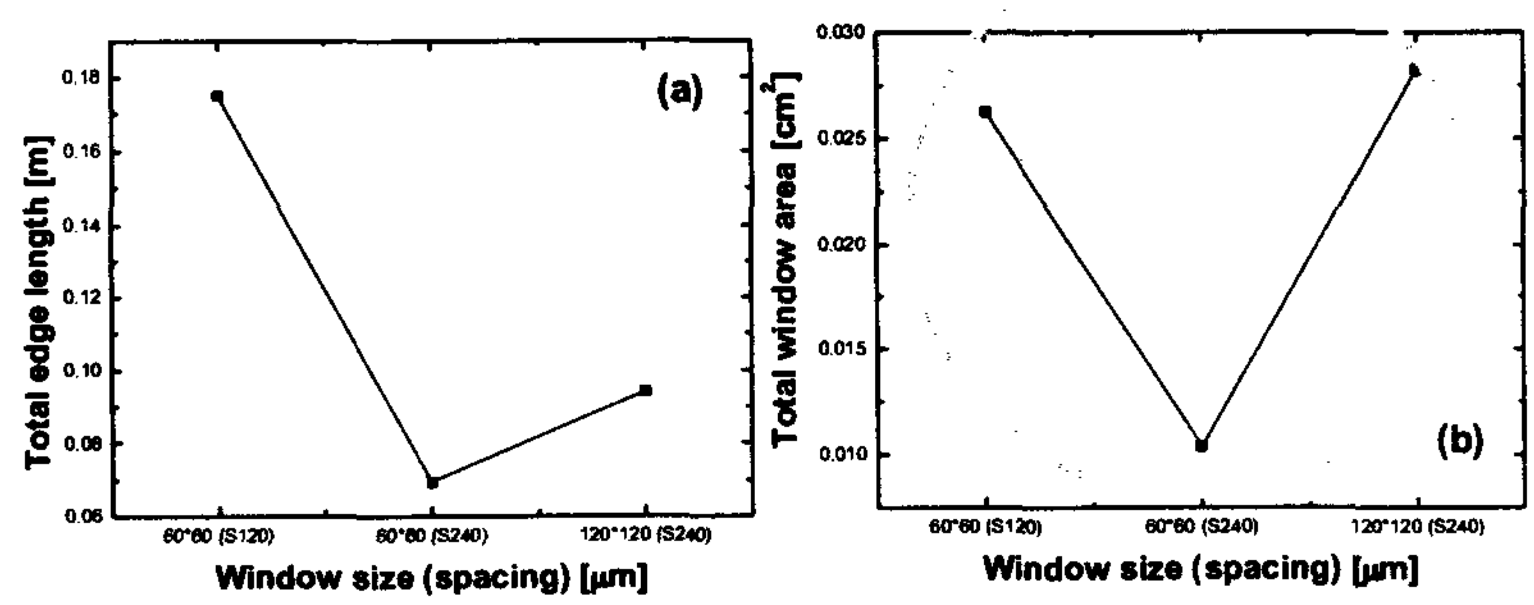


Fig. 4. Calculated morphological factors for patterned CNTs samples of (a) total edge length and (b) total window area.

6. References

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