ABSTRACT

We demonstrate the feasibility of a novel method to deposit individual carbon nanotubes (CNTs) at desired locations. The concept integrates the deposition of CNTs by dielectrophoresis onto a fountain-pen setup. Herein, we show the successful deposition of individual CNTs on two-point electrode gaps. Our approach goes in the direction of realizing fully automated manufacturing processes of CNT-based nanodevices. Furthermore, an integrated post-processing soldering step lowering the electrical contact resistance between the deposited CNT and the electrodes is discussed.

Keywords: carbon nanotube deposition, dielectrophoresis, fountain-pen

1 INTRODUCTION

The rapid progress in the research of nanomaterials drives the creation of novel methods and devices in which the advantages of the established silicon chip technology are exploited in combination with the potential of special nanoparticles such as nanowires and carbon nanotubes (CNTs). To this end, several research groups demonstrated the feasibility of CNT-integrated field-effect transistors [1,2]. An obstacle for the realization of CNT-integrated devices is the precise, reliable and high yield integration of CNTs in electric circuits and other MEMS. Current research in nanotechnology is concerned with the precise handling of individual CNTs [3,4]. Our goal herein is to contribute a simple, mass production capable method to assemble CNT-integrated electric circuits and subsequent precise soldering of the electrical contacts of these circuits. This is done by combining the method of dielectrophoresis (DEP) with a fountain-pen setup.

2 DIELECTROPHORESIS

An electric dipole exposed to an electric field aligns parallel to the electric field lines. As long as the electric field is homogeneous, no net force acts on the electric dipole. In an inhomogeneous electric field, the non-uniformity of the electric field exerts a net force on the dipole. The force on an electric dipole exposed to an electric field can be described by

\[ F = (p \cdot \nabla)E \]  

Therefore the net force \( F \) on the particle is a linear function of the electric field gradient \( \nabla E \) and the dipole moment \( p \) [5].

An electric dipole is induced to an uncharged polarizable particle subjected to an electric field. The resulting net force on the polarized particle in a non-uniform electric field is the dielectrophoretic force \( F_{\text{DEP}} \).

The induced dipole moment \( p \) of a particle dissolved in a liquid dielectric depends on the geometry of the particle, the external electric field and the solvent. The geometry of a CNT can be assumed to be a long prolate spheroid. This gives an induced dipole moment which is described by [6,7]

\[ p = \frac{1}{2} \pi r^2 l \varepsilon_m \text{Re}(K)E \]  

In equation 2, \( r \) and \( l \) are the radius and the length of the CNT, respectively, \( \varepsilon_m \) the absolute permittivity of the solvent, \( E \) the external electric field and \( \text{Re}(K) \) the real part of the complex polarization factor.
The complex polarization factor $K$, which is known as the Clausius-Mossotti factor for spherical particles, depends on the complex permittivity of the medium and of the particle. Equation 3 describes $K$ for an elongated particle aligned to the electric field $[8]$

$$K = \frac{\varepsilon_p - \varepsilon_m^*}{\varepsilon_m^*}$$

Here the absolute complex permittivity of the medium $\varepsilon_m^*$ and the particle $\varepsilon_p^*$, respectively, can be expressed as follows $[9]$

$$\varepsilon = \varepsilon - i \frac{\sigma}{f}$$

Where $i = \sqrt{-1}$, $\sigma$ is the electric conductivity and $f$ is the frequency of the external electric field. For a perfect dielectric ($\varepsilon >> \sigma$), the absolute complex permittivity $\varepsilon^*$ approximately equals the absolute permittivity $\varepsilon$.

The direction of the dielectrophoretic force relative to the electric field is denoted by $K$. A positive $K$ means that the particle is moved to the region of high electric field strength. A negative $K$ means that the particle is forced to the region of low electric field strength.

Due to the frequency dependency of $\varepsilon^*$, the complex polarization factor $K$ is a function of the frequency. From equation 3 one can derive two extrema:

$$f \rightarrow 0: \text{Re}(K) = \frac{\sigma_p - \sigma_m}{\sigma_m}$$

$$f \rightarrow \infty: \text{Re}(K) = \frac{\varepsilon_p - \varepsilon_m^*}{\varepsilon_m^*}$$

If the electric conductivity of the solvent can be neglected, the frequency dependence of $K$ is only governed by the frequency dependence of $\varepsilon_p^*$.

Applying a biased ac field, the time-averaged dielectrophoretic force comes out to be $[6]$

$$\langle F_{\text{DEP}} \rangle = \frac{1}{2} \pi r^2 \varepsilon_m \text{Re}(K) |E|^2$$

### 3 EXPERIMENTS

For the CNT deposition, a low concentrated CNT-water suspension was introduced into the micropipette of the fountain-pen setup. The micropipette was manufactured from borosilicate capillary tubes in a pipette puller (Zeitz DMZ Puller). The puller was programmed to deliver micropipettes with tip openings in the range of some micrometers. With $x$-, $y$- and $z$-axis translation stages the micropipette tip opening was placed precisely above an electrode gap on a silicon chip where an individual CNT was to be deposited. Applying pressure to the micropipette, a microdroplet of CNT-suspension was squeezed out of the opening. Subsequently, the pipette was moved down in the $z$-axis direction until the droplet touches the substrate surface. Due to the fountain-pen principle $[10]$, the microdroplet on the substrate surface is maintained despite evaporation, by a constant flow of CNT-suspension from the inside of the pipette. At the moment a microdroplet has formed on the substrate surface above the electrode gap (figure 1), the ac voltage was switched on and the DEP was initiated. The voltage was applied for a time interval of 60 seconds.

![Figure 1: The picture, taken with a CCD camera, shows the micropipette placed over the electrode gap which is covered by a spherical droplet of CNT solution. At the same moment the ac voltage is applied to the electrodes for up to 60 seconds. The electrical configuration is also shown, depicting the potential configuration on the electrodes in blue ($\varphi_1$) and green color ($\varphi_2$).](image)

The fountain-pen DEP process described above is schematically depicted in Figure 2. The electric field inside the microdroplet attracts an individual CNT through the micropipette opening to the desired position above the electrode gap.
Due to the precise positioning of the micropipette opening over the electrode gap with translation stages, the confinement of the micropipette walls and the small droplet volume in which the DEP was carried out, CNTs are placed precisely and individually at the desired location. At the same time, most of the possible spaghetti-like-bundled CNTs are held back in the micropipette.

In combination with the soldering process described in ref. [11], a precise soldering of the fountain-pen deposited CNT is possible within the same fountain-pen setup. The integration of the soldering process allows the manufacturing of complete CNT-based nanodevices within one setup and process chain. Furthermore, the process has the potential to yield computerized manufacturing by automating the positioning of the silicon chip and the micropipette. This results in the possibility for a larger scale, automated assembly. Further research will investigate the possibility to combine the fountain-pen based deposition with four-point electrodes which have been described in ref. [12].

In summary, we presented a simple novel method capable of aiding the assemblage future CNT-integrated chips in a fully automated larger scale process.

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**REFERENCES**


Figure 2: Schematic of the presented method. The micropipette is placed above an electrode gap as depicted. The electrical field between the electrodes (light gray color) results from an applied potential difference ($\Delta \phi$). This field is indicated by the narrow white lines within the CNT (black lines) in the suspension (blue color).

After the voltage was switched off, the micropipette was retracted from the droplet. Instantly, the cut off of CNT-suspension supply initiates the shrinking of the droplet sitting on the substrate. The evaporation driven shrinking extinguishes the droplet within a few seconds.

**4 RESULTS & DISCUSSION**

The fountain-pen controlled DEP method was proven to be able to deposit CNTs precisely. Figure 3 depicts the successful deposition of an individual, multi-walled CNT over an electrode gap of approx. 400 nm.

Figure 3: A CNT of 45 nm diameter was successfully deposited by the fountain-pen method. The electrode gap is approx. 400 nm wide.

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