The power of polymer wrapping

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Publication date:
2018

Chapter 6

Are Semiconducting Single-Walled Carbon Nanotubes Promising for Industrial Applications?

6.1 Introduction

The goal of this chapter is to illustrate how the results obtained in this thesis can be implemented in a practical way to address the challenge of expanding the use of electronic devices for the wellbeing in our society.

The fast pace of technological developments and the heyday of the internet of things (IoT) create the opportunity of developing all kind of electronic devices to improve our life quality from different perspectives. For instance something trivial as your cellphone communicating to your coffee machine at what time your coffee has to be ready before going to work, or something important as your glucose sensor sending information to your hospital notifying them that you are in danger.

The internet of things requires wireless communication between different objects, and for this purpose, each device needs to be uniquely identifiable. Besides, each device needs to be able to receive and communicate data. For that reason, sensors and smart labels are crucial for the development of IoT. Many of this objects also need to be light and flexible, meeting in this wat the flexible electronic field.

The semiconducting carbon nanotube inks we have developed during my PhD have a remarkable purity, which allows the fabrication of high performing field effect transistors. In this chapter, I will discuss why and how s-SWNTs are appealing for the growing market of the internet of things and flexible smart labels. I will discuss the implementation of carbon nanotubes for the fabrication of RFID (radio frequency identification) labels as an example of a possible application in which carbon nanotube properties can enhance the performance of a commercial product.

6.2 Valorization

The first definition of valorization is the one refer to the increase in the value of capital assets through the application of value-forming labor in production.[1] However, in this chapter, valorization is not related to capital, and it is more about the impact created through the transfer of the acquired scientific knowledge. For the long-term application of the knowledge acquired during my PhD work, it is crucial to identify which current technological demands and needs can be satisfied with the SWNTs inks we have been optimizing and investigating.

Patenting is likely the most efficient way to protect intellectual property, as it gives the freedom to transfer knowledge and implement that knowledge into final products. When a new invention is patented, novelty needs to be proven, and it also has to be shown that the information has not been disclosed before in any type of publication prior to the filing date of the patent. In the scientific activity, every project produces knowledge that can potentially be patented. However, as we are amid several research groups investigating similar research topics worldwide, it is a challenge to prove the novelty of each result in the rapid flow of new publications.

Because of the reasons mentioned above, I want to point out that even though patenting is the safest approach to protect intellectual property and commercialize a product, it can be cumbersome and other ways can be still explored.

6.3 The market needs

In the last years the fabrication of flexible electronic devices has attracted a large deal of attention, and as a market, it is forecast to grow exponentially in the coming decades. The market for flexible electronics is expected to reach over $87 billion by 2024.[2] It includes an extensive array of different fields and applications such as printed glucose sensors for diabetes patients, which is just one example of a billion euro market that is starting to grow, [3] and shows the potential of this technology in the health sector. In the coming years, low-cost, lightweight and low-energy consuming technology will be essential within the developments around the Internet of Things and Big Data. These developments have opened a whole new market for cheap and low consumption devices such as memories, sensors, logic circuits and tracking devices.

In the market presented above, s-SWNT can be implemented in logic circuits and driving electronics for cameras and displays. However, considering the size and current state of development of the smart label market, I decided to focus this chapter on RFID (radio frequency identification) labels. These labels are used in large variety of applications such as vehicle and goods identification, and are also used in product and file management as well as in the textile and clothing industry.

RFID is a form of wireless communication that uses radio waves to identify and track labels which are attached to objects. An RFID label has three main parts, namely a substrate that holds all components together, an antenna that receives or transmits a signal, and an integrated circuit (IC) that makes decisions and provides memory to store data.

The challenge for the smart label market is to find cheaper materials to produce all components of the RFID at a large scale. At the same time, the new materials need to ensure high performance and the stability of the RFID label for the time of their use.

6.4 Why s-SWNTs?

Currently, the IC component of an RFID label is most of the time fabricated using silicon. Countless industrial facilities have been developed to process the silicon and increase its purity to prepare it for electronic devices. However, the purification of the material is lengthy and costly, and the technical requirements for the fabrication of silicon devices are high.

While silicon provides the reliability and scalability that we all know, it lacks the mechanical flexibility and the possibility to reduce further the manufacturing costs. The promise of printable electronics is that the scale-up can be performed in a similar fashion as printing newspapers. Examples of solution processable materials are conjugated polymers and small molecules. However, these printable semiconductors still display performance and stability far lower from the one of silicon.

Semiconducting SWNTs are a solution processable material from which it is possible to fabricate highly performing and robust FETs. The high mechanical and thermal stability of SWNTs is a further advantage that opens a broader set of application respect to the ones of Silicon.

6.5 Description of the s-SWNT ink market

The company Nanointegris, founded by Mark Hersam, offers a s-SWNT ink (**IsoSol-S100® Polymer-Wrapped Nanotubes)** with a shelf life of 6 months for a price of almost 900$ per mg. Since 2014 they have a patent pending for specialized dialkyl homopolymer to be used for the separation of semiconducting single-walled carbon nanotubes. But, they were not the first group to publish about the polymer wrapping technique. The first publication on that topic was released in 2007 by Nish *et al.* where they showed an s-SWNT selection process using a dialkyl fluorine homopolymer.[4]

Considering also the high number of publications on the topic,of which many of them are authored by our research group, the chances for Nanointegris to obtain a patent for the IsoSol-S100® Polymer-Wrapped Nanotubes are significantly low, which opens the possibility of a free market.

In a free market, the price/quality relation play a fundamental role. For Nanointegris the focus is research groups and the commercialization of small amounts of inks. In that context, they are successful, even though the price per mg is high considering the cost of the materials needed in the process of selecting the s-SWNTs. In an open market, our strength is the knowledge gained in the fabrication of electronic devices and the implementation of different inks with specific properties in electronic devices. Our target market would be the growing flexible electronics industry.

6.6 What is needed to use s-SWNTs for printable electronics?

Initially, we will need to build a working prototype that shows clearly the potential of s-SWNT as building blocks for ICs which are the main component of RFID labels. A flexible device able to work at a frequency of 13,56 MHz and to handle bending will be the proof of concept. Similar prototypes have already been reported in the literature.[5] The working frequency of 13,56 MHz is used in RFID for pharmaceutical supply chain, libraries, protection of consumer goods among other applications.

After the potential of s-SWNT is proved, the first step to implement the use of s-SWNT inks for fabricating IC in the industry is to scale up the production of our inks to fulfill the volume requirements of industrial applications.

During our projects, we produced quantities of inks according to our needs. The production of 10 ml in one day provided us with material to perform experiments for a couple of months. For industrial applications, the production needs to be upscaled from milliliters per day to liters per day.

In our small-scale procedure, the main steps of the ink preparation are solubilization of the polymer, sonication of the polymer:SWNT complex, and centrifugation of the mixture of polymer and carbon nanotubes sample to separate the semiconducting SWNTs from the metallic SWNTs. For the solubilization, we used a small hot plate that costs a couple of hundred euros. For the sonication, we used a high power ultrasonicator (Misonix 3000) with cup horn bath, and a PID controller to set the temperature. The cost of the sonication system is approximately 10k euros. Finally, for the centrifugation step, we used an ultracentrifuge (Beckman Coulter Optima XE-90; rotor: SW55Ti) which costs around 50k euros.

The equipment described in the previous paragraph allows us to produce a maximum of 20 ml each time we run the process, and the challenge is to provide liters of ink after one selection process. Considering that ultrasonic baths and ultracentrifuge systems are available in industrial scale, the cost of purchasing the equipment needed to produce higher quantities of the ink is the most significant barrier.

From the scientific and technological point of view, the upscale will require the re-optimization of the selection procedure for the new volumes. In particular, the second step of purification should be carefully considered, as this is the one that requires the fastest centrifugation. Depending on the polymer used on the application, the requirements on this last step could be eventually modified making the production less energy and labor intensive.

6.7 How to implemented carbon nanotubes in the production of RFID labels?

If we manage to fabricate, from our s-SWNT inks, high performing devices that work at 13,56 MHz, the next step is to find a strategical ally to further develop the implementation of the inks for the fabrication of RFIDs.

What we need is to strategically find a company willing to invest in the scaling up and to use our inks in the fabrication process of ICs for RFID labels. Two kinds of companies would be potentially interested in our product. One option is a partnership with an IC manufacturer like NXP, and the second option is to look for an electronic printing company like AGFA.

If the strength of the company is the fabrication of ICs, this type of ally can offer a clear view of the market of RFID devices and also a strong network among companies that use smart labels as part of their products. In addition, experience in the manufacturing of ICs provides knowledge to identify the parameters that the ICs fabricated from s-SWNT need to fulfill. If the company has no experience working with solution processable materials, the design of the printing process to manufacture IC starting from inks will be the primary challenge of the partnership.

A company with experience on electronic printing could also be interested in our inks. For such a company would be easy to determine which characteristics of the ink are essential to have a homogenous and successful printing process at industrial scale. For this partnership, less experience in the fabrication of ICs, implies that the main challenge would be to implement a fabrication process of IC starting from the printed s-SWNT.

Even though both approaches present challenges, both are viable and open different possibilities to access the market. The main objective is to find an ally willing to put effort into the implementation of s-SWNT for the fabrication of electronic devices at industrial scale.

The exciting properties of SWNTs combined with the potential of low cost and large-scale fabrication of IC for RFID labeling have the potential to influence the market of flexible electronics.

6.8 Conclusion

Semiconducting SWNT inks present a massive opportunity for flexible electronics industry and RFID for the internet of things. The first step to implement carbon nanotubes as part of flexible devices is to ensure the possibility of their commercialization without patent problems. After, an IC prototype needs to prove all the potential of the s-SWNT inks. For the use of the inks at industrial scale, there is a need to scale up the production of s-SWNT inks. Finally, the inks need to be implemented in the fabrication process at industrial scale of electronic components.

The information provided on this thesis about the preparation of s-SWNT inks and the interaction of polymer and carbon nanotubes, provide knowledge to strive for the implementation of s-SWNT inks for the production of electronic devices at the industrial scale. The challenge is to find the right business partners that share common objectives and that complement our expertise.

Considering that the long-term use of our inks in the industry is feasible, and the target market is broad. The recognition of the right business partner is the door to enter into the business of flexible electronics.

6.9 References

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