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Electronic Devices Based on Printed Silicon Nanoparticles

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The use of silicon nanoparticles allows printed electronic to go beyond the simple printing of conductive materials. In our approach we use high quality silicon particles to replace the pigments in a graphics ink, and print semiconducting patterns together with conducting tracks and insulators to form electronic devices. The silicon nanoparticles are produced by high energy milling, which yields a particle size of about 80 nm. High resolution transmission electron microscopy (HRTEM) reveals that the nanoparticles have no noticable silicon dioxide layer. Due to their surface structure, the particles are not insulating, but allow charge transport from particle to particle so that the essential semiconducting features of silicon are maintained. Using these particles an ink has been developed which can be applied in a simple screen printing process. This ability to print silicon nanoparticles has enabled us to fabricate field effect transistors and recently also negative temperature coefficient thermistors. A short overview of the printed silicon technology and its applications will be given.

Keywords: Silicon, Nanoparticles, Printed silicon.

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1. INTRODUCTION

Printed electronics is a new, fast growing sector in the electronics landscape, which introduces into the already existing high integration of microelectronics and display technology using silicon thin film based transistors, new dimensions which make electronic devices, such as cell phones, more robust and even mechanically flexible [1]. Important milestones for this development are new materials like printed organic semicondutros [2,3,4] and metal oxide semicondutors, such as ZnO [5,6]. Printing of functional materials is of interest in a variety of fields including displays, electronics, optics and sensors due to the capabilities of low cost solution-based processing and direct writing at low temperature [7]. The use of nanoparticles in functional printing inks is motivated by the fact that nanoparticles already have all the required electrical and optical properties and can be used as simple building blocks to form complex structures at a small scale [8]. Novel materials on the nanoscale which are solution processible are crucial for these developments. In this paper we present the use of nanoparticles to produce hand mixed, customized inks for conductive tracks and more importantly novel, high quality silicon nanoparticles for active semiconductor layers and their application in electronic devices.

2. EXPERIMENTAL DETAILS AND RESULTS

For the production of the silicon nano-particles high energy mechanical milling was used. The feedstock for the milling process were Prime grade Boron doped silicon wafers with a nominal resistivity of < 0.005 Ω·cm. The wafers are milled for 1.5h employing a high energy laboratory disc mill. Image J, an image analysis freeware package, was used to calculate the size distribution of the silicon nano-particles from SEM micrographs. Using this technique nanoparticles with a log-normal size distribution with a median of around 80nm were produced, as shown in Fig. 1. High-resolution transmission electron microscopy (HRTEM) was employed to show the internal structure and the surface of the silicon nanoparticles. Fig. 2 reveals that the milled particles are polycrystalline with structural defects such as dislocations in the grains. More importantly there is no significant oxidation on the surface of the silicon nanoparticles which is important for their electrical properties and consequently for their use in electronic devices.

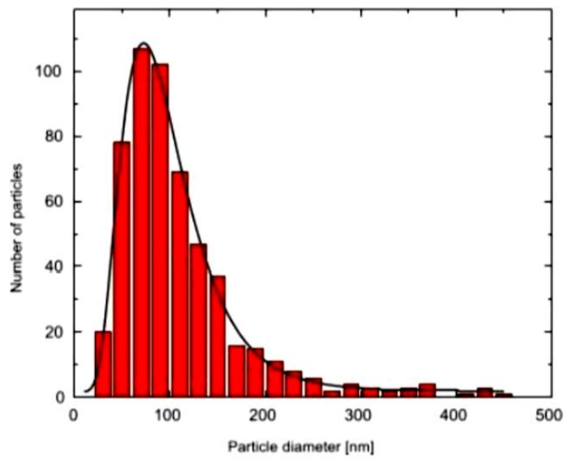

Fig. 1 – Size distribution of milled silicon nanoparticles

Conducting particles, such as silver, used in inks to print the conductive tracks were purchased from Sigma-Aldrich. Silicon and silver based inks suitable for screen-printing were produced and deposited on paper substrates using an ATMA AT-60PD semiautomatic screen printer. Crucial for the successful printing is that the inks meet certain rheological properties. The ink has to flow through the screen by the force applied by the squeegee during the printing process, but be thixotrophic

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to achieve defined edge definition necessary in electronic printing [11]. Mixing of the different particles with a water based acrylic binder, provided by Marchem Pty Ltd. South Africa, provided easily printable inks.

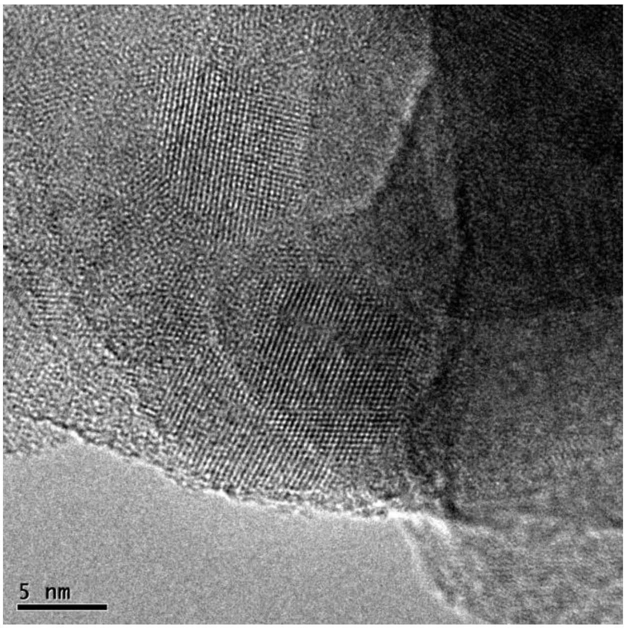

Fig. 2 – HRTEM micrographs showing the internal structure of the silicon nanoparticles

Table 1 – Sheet resistivity (Ω/sqr) of the different nanoparticles printed on paper substrate.

Sample	Particle loading	Sheet resistivity (Ω/cm)
Ag (calendered)	60	1.35
Ag (not calendered)	60	10.45
Ag (calendered)	50	$4.92\diamond10^{6}$
Ag (not calendered)	50	not conducting

For comparison of electrical properties inks with different particle loadings where prepared. For the conductive inks particle loadings of 50% and 60% in mass respectively have been used. Table 1 summarizes the electrical characteristics of the different silver inks, which shows that for inks above 60% particle loading the printed layers are above the percolation threshold and have excellent conductivities when calendared. The ink making procedure employed for the silicon nanoparticle ink follows a similar method used for the conductive inks using the same binder. The mechanically most stable printed layer was achieved by using 80% particle loading of Si-nanoparticles by weight.

The performance and a Photograph of a fully printed field effect transistor fabricated on paper substrate is shown in Fig.3. Without performing any post processing steps, such as sintering and calendering, transistors with performance characteristics comparable to amorphous silicon thin film transistors have been produced [10]. The printed FETs operate with drain and gate potentials lower, than 10 V, with drain currents in the range of microamperes. The electrical characteristics of the devices were determined using a Keithley 4200 SCS.

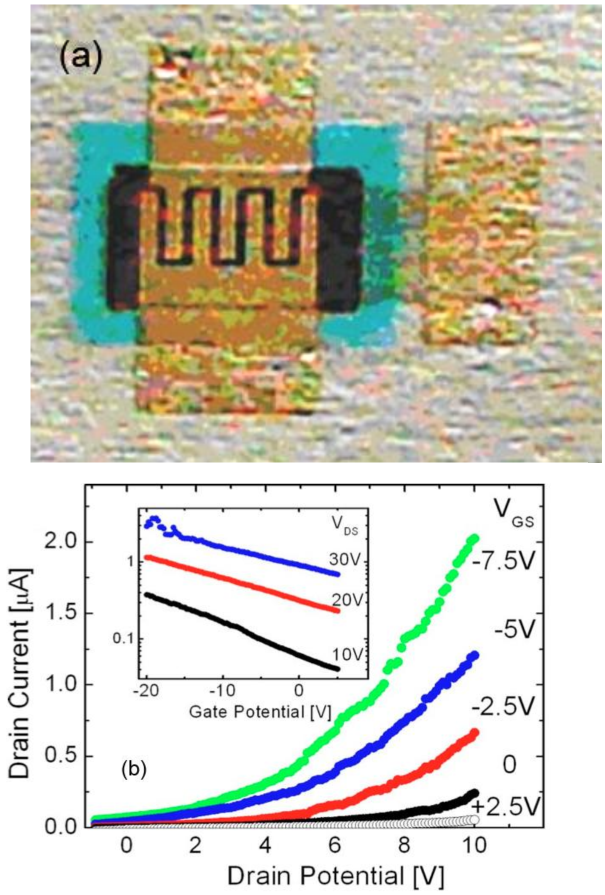

Fig. 3 – (a) Photograph of a bottom gate FET fully screen printed. (b): Output characteristics of silicon field effect transistors on paper substrates with the transfer characteristics as Inset

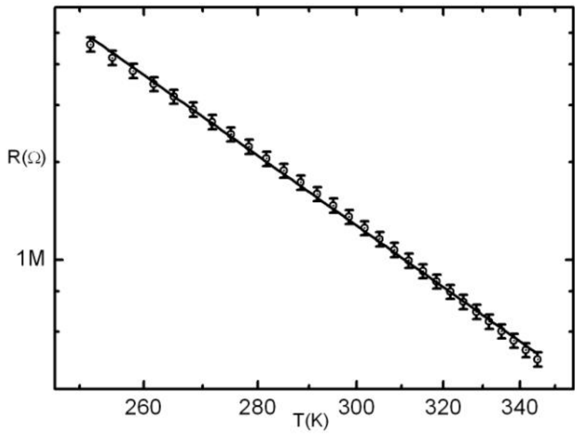

Fig. 4 – Temperature behavior of structure of this template corresponds to the article's one and text formatting realized due to the using of special styles, designed for these purposes

Another application for our printed silicon technology are negative temperature coefficient (NTC) thermistors. These were produced by a two color print, using printed silver tracks as the conductive and silicon nanoparticles as the active layer. The NTC thermistors produced do not need any post processing steps either. The Electrical characterization of the thermistors were performed with a Lake Shore Hall measurement system. The performance for temperatures from 250 K to 345K are shown in Fig. 4. The solid line presents the model fit using a least square fit with statistical weighting of the residuals and a Levenberg-Marquardt algorithm. The ß-value obtained from the fit is (2400 ± 100)K.

The high quality silicon nanoparticles have also been used to print Schottky diodes, which has one ohmic and one non-ohmic contact to the silicon nanoparticles. The diode characteristics at an sample device are shown in Fig. 5.

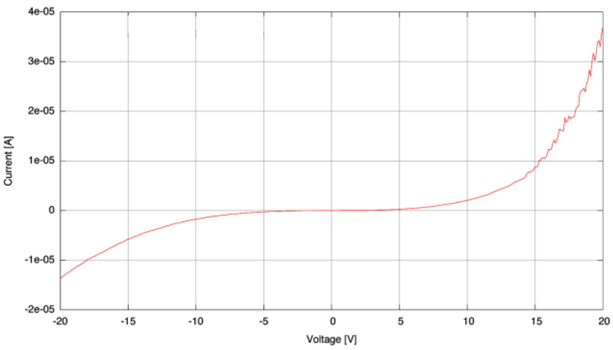

Fig. 5 – I-V curve of a fully printed Schottky diode

3. CONCLUSION

We have demonstrated that our high quality silicon nanoparticles can be used for various application in printed electronics. The use of silicon nanoparticles as the active layer in electronic materials, which can be printed using simple techniques on low-temperature substrates, such as paper, brings a great advantage for producing flexible electronics.

Moreover we showed that the resistances of customised inks, produced in our laboratories are comparable with those of commercial available inks.

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