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TECHNICAL REPORT

Nanoscale electrical contacts and interconnects

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NANOSCALE ELECTRICAL CONTACTS AND INTERCONNECTS

FOREWORD

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IEC 62632, which is a technical report, has been prepared by IEC technical committee 113: Nanotechnology standardization for electrical and electronic products and systems.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
113/135/DTR	113/167/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

The purpose of this technical report is to assess the current status of nanoscale contacts and interconnects, and to provide a basis for establishing international standards with the goal of accelerating innovation in nano-electrotechnology.

Nanoscale contacts and interconnects are expected to constitute challenges for many applications of nano-electrotechnology. The commercial success of many nanoscale electrotechnical subassemblies for electrical, optical, and magnetic products and systems will require contacts or connections to micro- and macroscale devices and systems. Present instrumentation used to characterize and view nanoscale contacts in three dimensions is not adequate for accelerating innovation and therefore commercialization. The standards and measurement methods associated with such instrumentation, and the theories used to interpret measurement results make it difficult to assess performance, reliability, and durability of subassemblies with enhanced functionalities based on nano-electrotechnology.

Nano-electrotechnology stakeholders tend to prefer those standards for nanoscale contacts that are technology- and material-neutral. Promoting standards that are too nano-electromaterial- and process-specific may impede creativity and innovation. Those developing nano-electrotechnology standards will face challenges to achieve balances among standards for nanoscale contacts that are applicable to many applications (DC, AC, and RF) and that are applicable to only a few specific materials with limited applications (e.g. digital).

Nano-electrotechnology is part of nanotechnology. They are often cross-sectional technologies with the potential for many cross-disciplinary applications. From the perspective of the International Electrotechnical Commission (IEC), nano-electrotechnologies include the following areas at the nanoscale: nanostructured sensors; nano-electronics, nano-materials, and nano-devices; optoelectronics; optical materials and devices; organic (opto)-electronics; magnetic materials and devices; radio frequency devices, components and systems; electrodes with nanostructured surfaces; electrotechnical properties of nanotubes/nanowires; analytical equipment and techniques for measurement of electrotechnical properties; patterning equipment and techniques; masks and lithography; performance, durability, and reliability assessment for nanoelectronics; fuel cells; and bio-electronic applications.

The economic significance of nanoscale contacts and interconnects is considerable. Introducing integrated circuits (IC) with higher density increases computing speed and reduces the cost of components for computing and a wide range of applications. If the rate of technology innovation were to slow dramatically due perhaps to the performance, reliability, and durability of nanoscale contacts, there could be a slowing in the introduction of new computing and consumer electronics. This could in turn reduce growth in the semiconductor sector and could have a negative ripple effect in other sectors that depend on semiconductors. Such a decline could have considerable productivity implications for all global economic sectors that rely on semiconductors. Furthermore, if the nanoscale contact processes have unacceptable variations, the yield for circuits may become too low for traditional business models. This would dramatically increase the cost of products, make the new technology more costly, and reverse the 4-decade-old deflationary trend in the semiconductor industry – namely, the substantial decrease in cost per function with each new technology generation.

The development of standards for nano-scale contacts and interconnects will often occur in the context of one or more of the following business models for nano-technologies:

a) Traditional business model

   Research and development supported in part by grants lead to new technologies for prototype product development followed by building manufacturing capacity, deployment, and commercialization. This model may not be appropriate for nano-electrotechnologies because it is very capital intensive and takes too long for commercialization with investors, who often want financial success (positive returns on their investments) quickly.

b) Solution-looking-for-a-problem-or-market business model

Research and development leads to new technology that may have phenomenal commercial success or more likely may remain as an interesting technology sitting on a shelf. Commercialization challenges include, in part, the following:

1) it usually takes a very long time to integrate a specific nano-electromaterial into large-scale industrial processes that customers appreciate and want;
2) markets for specific nano-electromaterials are limited even though the market for the application of the related technology may be large; and
3) costs associated with scaling from the R&D prototype volumes to commercial manufacturing volumes are considerable.

In the context of standards developers, this may not be an optimum model for nano-electrotechnology stakeholders.

c) Penetrate existing markets model:

Based on what the customer wants or on increased functionality for the given application:

1) use core competencies in nano-electrotechnologies to penetrate existing markets and develop nano-electrotechnical subassemblies directed at increasing functionality with lower cost-per-function for specific applications;
2) build a large nano-electrotechnical subassembly portfolio for a positive revenue stream;
3) invest a reasonable portion of profits to develop unique processing capabilities that will maintain a diverse portfolio, while manufacturing some high-volume nano-electrotechnical subassemblies;
4) establish joint ventures and partnerships from the start with organizations that are financially sound and already have access to large markets; and
5) combine efficiently for all stages of subassembly development and commercialization the forces of market pull and technology push, with an emphasis on market pull.

A detailed analysis of the broad implementation of nanomaterials in applications has identified a number of products expected to reach the market in the near future. Some of these products have already emerged from research and are on the market. Because there are so many products being developed that might incorporate nanomaterials, the focus of this report had to be intentionally restricted.

Nanoscale contacts can be formed in many ways, and could have applicability in a variety of products and applications. In particular, contacts may be useful in electrical, optical, magnetic, chemical, and mechanical applications. To limit the scope of this technical report, products and applications have intentionally been restricted to electrical and optical contacts or devices. For the most part, nanoscale contacts covered in this report are restricted to a macroscopic conductor making some contact either directly to a nanoscale contact and then to a nano-object, or making connection to a bulk material that then makes a nanoscale contact to a nano-object.

An analysis of the use of nanomaterials in components and products was conducted. In the analysis, publicly available roadmaps on nanotechnology were reviewed in detail and mind maps were developed that showed the likely use of nanomaterials in nanocomponents, that ultimately nano-enable a product. Through a thorough review of the roadmaps, and through a thorough review of marketing projections, a small number of product applications were highlighted as the focus for this technical report. The product areas of focus include:

– semiconductor devices and integrated circuits: nanoscale contacts and interconnects to the devices on the wafer surface (including the use of graphene);
– OLED lighting and displays (polymer to nano-object contacts, nano-composite materials);

– products that used metal-to-nanowire contacts (including graphene sheets to nanowire via interconnects);
– photovoltaic products (use of nano-objects in PV products to conduct current or to enhance solar efficiency);
– printable electronics, flexible electronics, and flexible displays;
– batteries (lithium-ion and ultra-capacitor products); and
– solid-state lighting (using quantum dots for improved efficiency).

Although many other products and applications exist today that are using a variety of nanoscale contacts and interconnects, it is believed that the above categories highlight some of the most likely candidates that are either on the market today or may be soon. This technical report will restrict itself to this scope, with the expectation of expanding to other products and applications in the future.

It was also difficult in many cases to find published research results concerning any nano-contacts and nano-interconnects related to the various product areas listed above. In particular, the published literature primarily included coverage of CNTs (carbon nanotubes), CNFs (carbon nanofibres), nanowire-to-metal interconnects and graphene interconnects. There was very limited coverage of nano-contacts and interconnects in organic materials to III-V semiconductors such as GaAs, and in magnetic structures. All of these technologies are discussed in this technical report. Due to a lack of published literature related to PV products, printable electronics, batteries and solid-state lighting, those technologies are not discussed in great detail in this report, but may be added in the near future as research reports are published.

Another part of the scope of this technical report relates to measurement techniques used with nano-contacts and interconnects. Throughout the review and analysis, measurement techniques were identified that might benefit from IEC TC113 standards development. This TR provides a summary of potential standards development activities that would enable the nanotechnology to move forward toward greater market penetration.

Two types of nanoscale contacts and nano-interconnects emerged as the most important components to the nanotechnology industry: nanotube interconnects and graphene. These two types of electronic contacts have become critically important to the semiconductor industry in recent years. As the scaling of semiconductor devices continues toward smaller and smaller sizes, circuits have run into limits on the conductivity of copper interconnects and their contacts. The semiconductor industry has started to invest a great deal of money and time into research on graphene and nanotube interconnects in hopes of finding a technology that will help extend Moore's law for a number of additional generations or "technology nodes." Graphene has showed promise in this regard, and appears as the major technology that might extend Moore's law for semiconductor interconnects. Due to this increased interest, many researchers have been studying this material and contacts to graphene. A major part of this TR is therefore devoted to graphene technology, and a good part devoted to nanotubes. Vertical nanotubes may be used to connect horizontal graphene sheets in the vertical direction on an integrated circuit or printed circuit board.

NANOSCALE ELECTRICAL CONTACTS AND INTERCONNECTS

1 Scope

This technical report describes a variety of nanoscale contacts and nano-interconnects used in research and development and in present-day products.

The intent of this technical report is to identify nanoscale contacts and nano-interconnects that will be common in products, to describe the state-of-the-art and to describe some key features and issues related to these contacts. In particular, the following are discussed in each of the nanoscale contacts or nano-interconnects discussed in Clause 5:

– type and configuration of the nanoscale contacts and interconnects formed;
– requirements of the nanoscale contacts and interconnects in products;
– fabrication technologies, processes, and process controls used to make the nanoscale contacts and interconnects;
– characterization techniques used to quantify nanoscale contacts and nano-interconnects;
– functionality and performance of nanoscale contacts and interconnects;
– reliability of the nanoscale contacts and interconnects in products; and
– expectations of when the product and the associated nanoscale contacts will reach the market.

This technical report points out the positive and negative characteristics of the nanoscale contacts and interconnects in each technology or nanomaterial discussed. This information may be helpful to product designers and researchers in their efforts to bring other nano-enabled products to the market. Recommendations for the formation and use of nanoscale contacts and interconnects are also indicated.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/TS 27687:2008, *Nanotechnologies – Terminology and definitions for nano-objects – Nanoparticle, nanofibre and nanoplate*

ISO/IEC 80004 (all parts), *Nanotechnologies – Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO/TS 27687:2008 and ISO/IEC 80004, as well as the following apply.

3.1
nanoscale contact
interface between a conductor or conductive bulk material and a nano-object that can pass energy in the form of either current or light

3.2
nanoscale interconnect
a series of conductors or conductive bulk materials connected together by nanoscale contacts that can pass energy in the form of either current or light

4 Framework of the technical report:

This clause addresses the identification of product applications and technical experts, and creation of questions addressed with respect to the various nanoscale contacts and nanoscale interconnects discussed in this technical report.

A process was followed to identify technical experts in the field of nanoscale contacts and nano-interconnects. Initially, a large group of attendees who had participated in a Materials Research Society (MRS) workshop (in 2010, San Francisco) on nanoscale contacts and interconnects were approached. Through personal email contact, nearly a dozen of these individuals agreed to discuss issues related to contacts and interconnects with the author of this technical report (TR). Additionally, these individuals recommended or provided many documents to be used in this TR. A bibliography is included at the end of the TR and is referenced throughout this report.

From the discussions with technical experts, the following list of concerns and questions related to nanoscale contacts and nano-interconnects was formulated. These questions informed the general discussions that took place and focused the attention of the TR on these issues. Throughout the TR, many of these questions are addressed in general, and sometimes specifically.

– What are the types and configurations of the nanoscale contacts formed?
– What types of nanomaterials are used in the product?
– How are these nanomaterials contacted?
– What is the conductor or conductive bulk material used?
– Between which materials (two or more) is the nanoscale contact formed?
– Are there multiple nanoscale contacts in the overall configuration?
– What are the requirements of the nanoscale contacts in products?
– What is the purpose of the nanoscale contact in the product?
– Is the contact meant to pass current? How much?
– Is there an expectation that light will be generated from the nanoscale configuration?
– What are the electrical specifications for the device and in particular the nanoscale contacts?
– Are there other specifications that relate to temperature, environment, voltage, current, frequency, geometry of contact, number of contacts formed, transparency, mechanical and chemical stability or other critical parameters?

• <u>Fabrication technologies, processes, and process controls used to make the nanoscale contacts</u>

– How are nano-scale contacts fabricated or manufactured?
– What process steps are used to fabricate contacts or interconnects?
– What incoming requirements are there related to the nanomaterials used?
– What control processes exist to repeat the process successfully every time the product is manufactured or fabricated?
– Are there special treatments of the nanomaterials used prior to incorporation into the device?

– Are there special post fabrication processes to insure quality nanoscale contacts, such as annealing, light activation, sintering, etc.?
– Are these devices or products being mass produced today, or are the efforts restricted to an R&D environment?

- Characterization techniques used to quantify a nanoscale contact:

– How are the nanoscale configurations characterized?
– Is there an effort to fully characterize the nanoscale contacts formed?
– What are the critical parameters being measured in the nanoscale contacts?
  - I-V characteristics?
  - Ohmic behavior?
  - Schottky behavior?
  - Frequency behavior?
  - Transparency required?
  - Mechanical robustness?
  - Chemical stability?
  - Other characteristics measured?

– What type of diagnostic analysis is employed to deeply understand the type and quality of the nanoscale contacts formed?
– What types of standards activities might be needed to help the industry with the manufacturing and characterization of nanoscale contacts and nano-interconnects?

- Functionality and performance of the nanoscale contacts

– Is the expected functionality from the nanoscale contacts observed?
– Do the nanoscale contacts meet all the requirements for the product?
– What efforts are being or have been made to improve the characteristics of the contacts?

- Reliability of the nanoscale contacts in the product

– Are reliability requirements established for the nanoscale contacts?
– How is reliability measured or characterized?
– Is accelerated life testing used in characterization? What are the results observed?
– Has any long-term aging been employed with the nanoscale contacts? What are the results observed?

- Expectations of when the product and the associated nanoscale contacts will reach the market

– Is the nano-enabled technology/product presently on the market?
– When is the nano-enabled technology/product expected to be on the market?
– What improvements need to be made to the nanoscale contacts and/or nanomaterials to make the technology/product successful?
– What are the plans for next-generation technology/products?

The framework above provides a comprehensive set of questions to be asked that aid in understanding nanoscale contacts and nano-interconnects. The technologies that were explored for this TR are summarized in Clause 5. Note that many of the above questions are not asked by the researchers in every technology effort presented below. Some research focuses primarily on fabrication and performance, while other types might look into reliability. No one paper discusses comprehensively all the areas listed above, but the literature as a whole does give us a good perspective of the pros and cons of the various technologies.