Toptalent

Application form (closing date 8 January 2008)

Complete this form in English or Dutch

Den Haag, August 2007 (versie 21/10/2007 / aantal pagina's 13)
Nederlandse Organisatie voor Wetenschappelijk Onderzoek

1 Basic details

1.1 Details of applicant

- Title(s), initial(s), First name: *A.M. (Stijn) Goossens*
- Male/female: *Male*
- Address for correspondence: *E. Th. a Thuessinklaan 21*
  9713JR Groningen
- Telephone: *06 - 26 220 168*
- E-mail: *amgoossens@gmail.com*
- Website (optional): -

1.2 Details of intended supervisor

Note! Separate letter of recommendation is required!

- Title(s), initial(s), First name, surname: *Prof. Dr. B. de Boer*
- Address for correspondence: *Nijenborgh 4*
- Telefoon (vast/mobiel): *050-363 4370*
- E-mail: *B.de.Boer@rug.nl*
- Website (optional): *me.fmns.rug.nl*

1.3 Host institution

University of Groningen (RUG)

2 Research proposal

2.1 Research field

- Sciences / technology (Chemistry, physics, mathematics, technical sciences, etc)

2.2 Title of research proposal

Molecular transistors: development of both a functional nanodevice and an analytical tool

2.3 Summary of research proposal

Nanofabrication techniques like self assembly are used to construct the first molecular transistor. The device is based on the MIMIM design and will not only be of practical use, but will also result in fundamental knowledge about molecular electronic transport.

(40 words)

2.4 Brief description of research proposal

Max. 2000 words (on max. 5 pages, including illustrations, references and footnotes), use the following structure.

2.4.1 Introduction

In 1960, C.A. Mead proposed a tunnel emission amplifier [7], which functions very much like a bipolar transistor. The device consists of a stack of three electrodes, with all electrodes separated by a very thin insulator, creating a metal-insulator-metal-insulator-metal (MIMIM) transistor. The device was expected to have a superior frequency performance of up to 3 TeraHz, but until now no research group has met this expectation.

Mainly due to the bad quality of both the metal and the insulting layers of MIMIMs made in the past, results were discouraging and the research in this area almost stopped. Recently, a group from Japan used lattice matched materials for barriers and contacts which resulted in an outstanding performance [1]. This device is encouraging for future work on MIMIMs, although it is not trivial making lattice matched molecular beam epitaxy structures. Fortunately, recent advances in nanoscience have led to the development of techniques and materials to give the MIMIM a prosperous future.

I believe the way to construct MIMIMs is to use the technique of self-assembled monolayers (SAMs) to make energy barriers of insulating molecules. SAMs are organic assemblies formed by the absorption of molecules from solution or the gas phase onto the surface of solids (metals). Self assembly is a very promising bottom-up nanofabrication technique because of nature’s spontaneous drive to find equilibrium in creating nanostructures. The single molecule thick structure (monolayer) will just form by itself. The ease of processing and the freedom in materials, both substrates and molecules, make the technique even more attractive.

Recently, researchers at the Zernike Institute for Advanced Materials (Groningen), in collaboration with Philips Research Laboratories Eindhoven, discovered how to electrically contact a SAM by using a device structure called large-area molecular junction, shown in Figure 1 and Figure 2 [2]. This large-area molecular junction is basically a MIM structure with a self-assembled monolayer of alkanedithiols as insulating barrier. The challenge is to construct two of these junctions on top of each other, and if this is done, in principle, the molecular MIMIM transistor is realized.

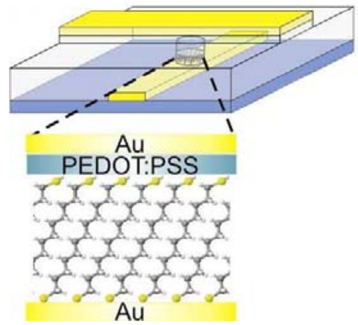

Figure 1 *Large-area molecular junction: the self-assembled monolayer of alkanedithiol molecules on gold bottom contact topped with a layer of conducting polymer (PEDOT:PSS) to prevent gold from penetrating the monolayer[2].*

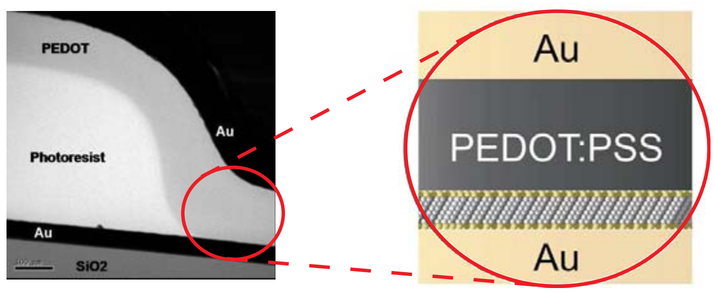

Figure 2 *SEM micrograph of a large-area molecular junction, with a schematically magnified overview of the junction.*

In Figure 3, the energy band diagram and working principle of a MIMIM transistor is shown. The MIMIM transistor should consist of a tunnel barrier, B_1, with a large barrier height and a small barrier width, and a tunnel barrier, B_2, with a small barrier height and large barrier width, as depicted in Figure 3. The emitter injects electrons in the base via tunneling through the first junction, B_1. These electrons are called hot electrons and traverse the base ballistically (without scattering). With the base-emitter voltage (V_{BE}) the relative height of the second barrier can be modulated and, consequently, the collection of the electrons by the collector is modulated. In Figure 3a V_{BE} is larger than the collector barrier, B_2, and the electrons are collected: the On-state. In Figure 3b V_{BE} is smaller than the collector-barrier, B_2, and the electrons are not collected and thermalize (are lost) in the base: the Off-state.

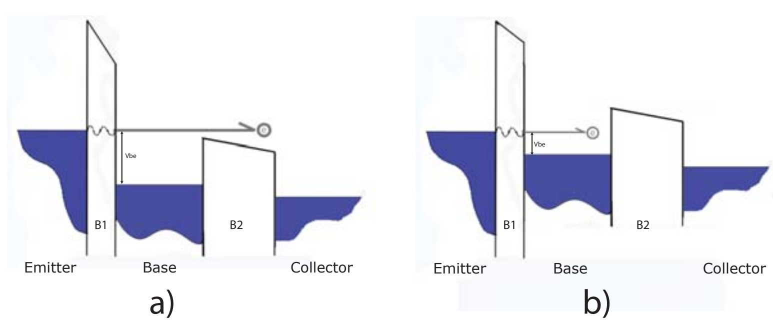

Figure 3 *Energy band diagrams of the MIMIM transistor a) V_{BE} > collector barrier B_2 b) V_{BE} < collector barrier B_2.*

Many fundamental questions about transport through single molecules remain unanswered. A new way to elucidate the transport mechanisms is to use the MIMIM as an electron energy spectrometer. Barrier B_1 functions as 'device under test' and barrier B_2 as detector. This makes the MIMIM transistor a very powerful analytical tool: I can directly probe the energy level dependent transport through molecules.

2.4.2 Research question(s)

The main goal of the project is two-fold:

1. to make a current amplifying device in the form of a MIMIM transistor by using two self-assembled monolayers as insulating barriers, and
2. to investigate the fundamental physics underlying the working principle of the MIMIM-transistor.

The goal can be subdivided in several challenges that have to be addressed.
-Can I find organic insulating molecules that self assemble and have the correct tunnel barrier heights and widths?
-Can I process two large-area molecular junctions on top of each other?
-Can I prove that the MIMIM transistor functions as a current amplifying device?
-Is the middle electrode (base) sufficiently thin to minimize scattering of electrons?
-How do different molecules in the SAM influence the characteristics of the MIMIM?
-What are the loss mechanisms in the MIMIM: interface reflections, phonon coupling, defect scattering or something else?
-Can I probe the energy level dependent transport of electrons through the molecules in barrier B_1?

2.4.3 Method / Approach

Structure and techniques

First, a structure for the MIMIM has to be devised. I need to find a way to stack two self-assembled monolayers of insulating molecules, separated by a thin metal electrode, the base (Figure 3). The base layer should be very thin (less than ~20 nm), otherwise the electrons in the base are scattered (non-ballistic transport) and the performance of the device degrades dramatically.
There are several routes to construct a molecular MIMIM with a thin base layer. I will start with trying to stamp the thin base layer directly on the SAM with a PDMS stamp, using a technique called nanotransfer printing [4]. On this stamped gold layer I will assemble the second monolayer of molecules (Figure 4). I will make the contact to this second layer of molecules with standard large-area molecular junction processing techniques.

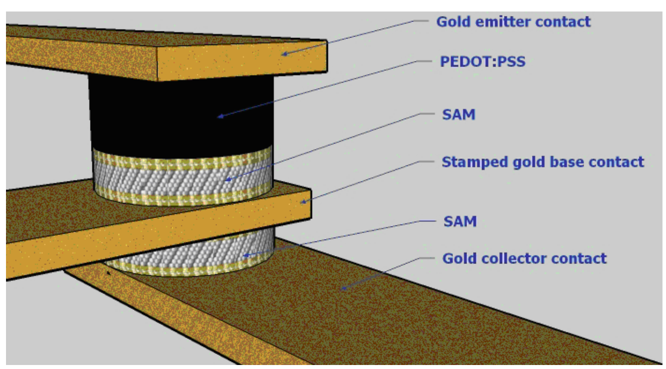

Figure 4 *Structure of the stamped base MIMIM.*

The second possible route is to use two large-area molecular junctions [2] mutually connected through their bottom contacts (Figure 5). This requires the ability to remove the large-area molecular junction from its substrate and to process another large-area molecular junction on the bottom of the first device. Possibly this can be realized by using a method called template stripping [3].

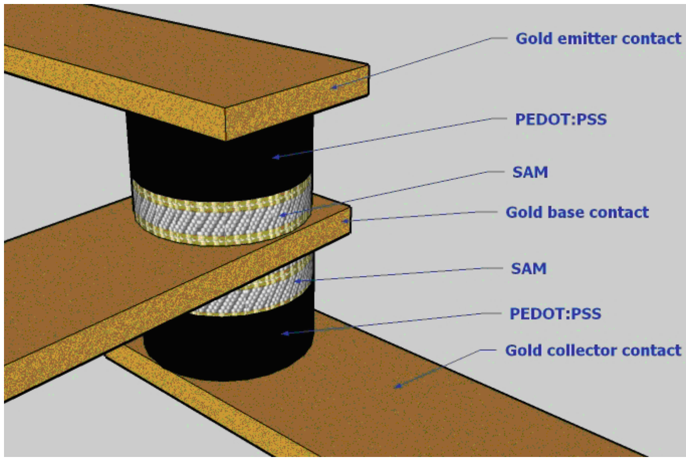

Figure 5 *Structure of the proposed MIMIM. Compared to Figure 1 this structure uses two mutually connected large-area molecular junctions.*

If these two elegant approaches do not result in reliable MIMIM transistors, a simple backup structure is available. This MIMIM does not use two SAMs, but just one. The other tunnel barrier is a silicon oxide barrier, which is easier to implement in the design. Standard highly doped silicon wafers can be used simultaneously as substrate and electrode on which a silicon oxide layer is thermally grown, creating the MI. The final MIM stack is processed using the conventional technology for large-area molecular junctions [3].

Materials

Some requirements for the barriers need to be met to make the device work well. The emitter-base barrier, B_1, has to be thin and high, so I can use simple alkane(di)thiols as their thickness is easily varied between 10-30Å and their barrier height is ~4 eV [5]. The base-collector barrier, B_2, has to be thick and low. Thick, because no leakage current should flow from the collector into the base and low, because as much electrons should be collected by the collector at a low applied potential, V_{BE}. Oligophenyl(di)thiols are good candidates. Before I can assemble Oligophenyl(di)thiols in the MIMIM I have to characterize them in two terminal large-area molecular junctions. By fitting the tunneling model from reference [5] to current voltage measurements, I can calculate the barrier height and the decay (or loss) coefficient of the molecules.

Characterization

The quality of the SAMs is crucial for the functioning of the MIMIM. Several standard surface science techniques are available for characterization of the SAMs: STM, XPS, contact angle, ellipsometry. The quality of the gold base layer is also of great importance: the layer should have no pinholes to ensure good transistor action and the roughness should be low to guarantee the formation of a good SAM. The quality of the gold layer can be checked by scanning probe microscopy techniques.
To investigate the fundamental physics of the molecular MIMIM transistor, I have to characterize the electronic transport through the device. One important parameter is the transfer ratio, which is defined as the collector current divided by the emitter current; a measure for the efficiency of transistors. For switching applications, I should measure the on/off ratio and cut off frequency of the molecular MIMIMs

Electron transport spectroscopy

The collector barrier functions as a high pass filter for the electrons (Figure 6). If J is the collector current and Φ the applied collector-base potential, the derivative $dJ/d\Phi$ is proportional to the energy distribution of the incoming electrons. So when I measure the collector current as function of the applied base-collector potential, I can calculate the energy distribution of the electrons emitted by the injector barrier (I supposed the velocity distribution of the electrons to be constant over the energy range). This energy distribution gives insight in the transport mechanism of electrons through single molecules.

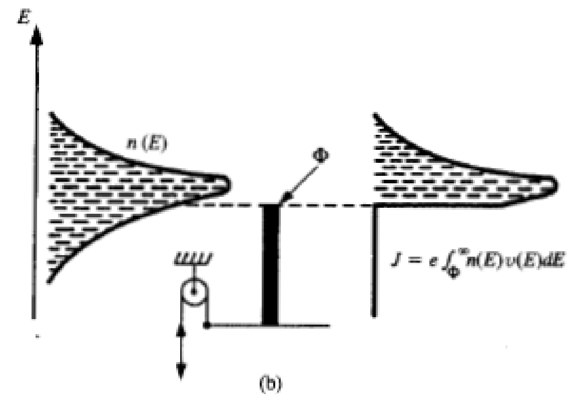

Figure 6 *A high pass electron energy spectroscopy device. Left: the energy distribution of the incoming electrons. Right: the energy distribution of the electrons that have passed the collector barrier with height Φ [6].*

2.4.4 Innovation

The MIMIM is a very powerful analytical tool since I can use it as an electron transport spectrometer, which enables me to elucidate the fundamental physics behind molecular electron transport, because I can probe transport through molecular levels directly. Something theoreticians have been waiting for a long time. C.A. Mead proposed the concept of a MIMIM almost half a century ago. Up to now no convincingly functioning MIMIM transistor has been published. I believe the molecular MIMIM is the solution to fabrication problems encountered before. Furthermore, the MIMIM structure is the only possible first step to realize integrated molecular electronic circuits. The other possibility to make molecular transistors is to use the field-effect transistor (FET) structure with a single molecule as channel. A requirement for this FET is that the gate-channel barrier thickness should be ~10% of the channel length: the barrier thickness should be 0.1 nm, which is impossible to realize.

I will apply recently developed state-of-the-art nanoprocessing techniques, like self assembly, nanotransfer printing, lithography and spin coating in this nanoscale electronic device. Self assembly of molecules provides the possibility to construct the thinnest possible device of one molecule thick. By using these new techniques, I will find new methods of stacking electronic components, which enables future molecular electronic chipmakers to make full use of the space in the 3rd dimension on a chip.

2.4.5 Relevance for science, technology or society

Developments in western society are for a large part driven by the hunger for increasing computing power. The direct road to faster chips is miniaturization.The current approach of the chip industry towards miniaturization is improving their lithography machines, but this method will encounter fundamental physical limits by ~2015. To meet the predictions of the famous Moore’s law, new ways to produce chips have to be found. One of the solutions is to use the inherently smallest functional building blocks available, namely: *molecules*. Molecules can be utilized as the functional electronic elements (or molecular electronics).

The fabrication of molecular MIMIMs promises to be cheap and easy, because of the use of self assembly and organic molecules as resources. Moreover, self assembly could be very environmentally friendly, because the solution with molecules can be used over and over, so no materials are wasted.

Along with developing a device with crucial importance for technology, I will redefine the horizon of the understanding of molecular electronic transport. The molecular MIMIM will be of vast importance as an analytical tool to the scientific community that is concerned with transport through single molecules.

2.4.6 Literature references

[1] W. Saitoh et al, *Jpn. J. Appl. Phys.*, **34**, L1254-L1256, 1995.
[2] H.B. Akkerman et al, *Nature*, **441**, 69-72, 2006.
[3] J.C. Love et al, *Chem. Rev*, **105**, 1103-1170, 2005.
[4] Y. Loo et al, *Nano Letters*, **3**, 913-917, 2003.
[5] H.B. Akkerman et al, *Proc. Natl. Acad. Sci.*, **104**, 11161-11166, 2007.
[6] M. Heiblum and M. Fischetti, *IBM J. Res. Dev.*, **34**, 530-549, 1990.
[7] C. A. Mead, *Proc. of the IRE*, **48**, 359-361, 1960.

Indicate the total number of words: *1993*

2.4.7 Plan of work / Werkplan

Briefly indicate for each calendar year which activities are planned

Year	Research activities
2008	-Find and characterize suitable barrier materials. At the RUG many materials are available through the extensive collaboration with the chemistry group of Prof. Ben Feringa.
2009	-Construct a working molecular MIMIM: design production process, learn production techniques, solve critical issues and implement knowledge in improved design. -Fundamental characterization of the MIMIM and its electron transport
2010	-Construct and improve MIMIM by varying molecules, and (inter) layers -Fundamental characterization of MIMIM and its electron transport -Study single molecule electron transport.
2011	-Study single molecule electron transport.
2012	-Wrapping up research, write thesis, defend thesis.

3 Cost estimates

8a. Budget

Costs	2008 sept-dec	2009	2010	2011	2012 jan -aug	Total[2]
Staff (in k€)						
Applicant[1]	13	41	43	45	34	176
Non staff (in k€)						
Benchfee (standard)						
Equipment						
Consumables	6	15	15	15	4	55
Travel		3	4	4	4	15
Other						
TOTAL[2]	19	59	62	64	42	246

1. The estimates for salary costs are based on the salary tables of the "CAO Nederlandse Universiteiten" (www.vsnu.nl). The numbers are advised and approved by the administration of the University of Groningen.
2. The total budget is in excess of the maximum of 180 kEuro that is set by NWO. This higher budget is guaranteed by the University of Groningen.

3.1 Costs exceeding the grant

The maximum amount of the grant is 180 k€. Costs exceeding the maximum grant must be met by the university.
University guarantees to meet additional costs and to provide support services and supervision.
Select:
– Yes,

The Zernike Institute for Advanced Materials supports	25 k€
The faculty Math. & Nat. Sci. support via ‘modelmatige bijdrage’	16 k€
The remainder is supported from the VIDI grant of the supervisor Dr. B. de Boer,	25 k€
Total support RUG	66 k€

3.2 Other Grants

No, I did not apply for any other grants, but part of the additional costs for the applicatant (see 3.1) will be covered by the recently awarded VIDI grant of Dr. B. de Boer entitled “Making molecular electronics reality with large-area molecular junctions”.

4 Curriculum Vitae

4.1 Personal details

Applicant	
-Title(s), initial(s), first name:	*A.M., Stijn*
-Surname:	*Goossens*
-Nationality:	*NL*
-Date of birth:	*17 March 1985*
-Country and place of birth:	*NL, Lichtenvoorde*
Parents	
-Country of birth father:	*NL*
-Country of birth mother:	*NL*

4.2 Secondary education

School type:	*Gymnasium*
City and country:	*Haaksbergen, NL*
Period:	*September 1997 - June 2003*
Graduation date:	*13 June 2003*

4.3 Bachelor's degree

University/College of Higher Education:	*University of Groningen*
Faculty/discipline:	*Applied physics*
City and country:	*Groningen, NL*
Period:	*September 2003 – August 2006*
Date Bachelor’s degree:	*31 August 2006*
Grade average:	*7.6*

4.4 Research master's

University:	*University of Groningen, Zernike Institute for Advanced Materials*
Faculty/discipline:	*TopMaster Nanoscience, an honours program in physics and chemistry,*
City and country:	*Groningen, NL*
Period:	*From September 2006*
Expected date Master’s degree:	*31 August 2008*
Grade average (so far):	*8.2 (no grade below 7, results in cum laude; TopMaster courses are graded much more stringent than normal master courses)*
Title Master’s thesis (if applicable):	*Electrical characterization of conjugated molecules in large-area molecular junctions: Towards MIMIM transistors*
Grade for thesis (if applicable):	-

4.5 Motivation for application (max. 80 words!)

Feynman's seminal paper 'There's plenty of room at the bottom' initiated my fascination for nanotechnology. Also electronics has always fascinated me, so the recently developed research in molecular electronics, thrilled me. Within the enormous possibilities in this field, the molecular MIMIM transistor is for me a fantastic, but achievable goal. The Toptalent grant allows me to contribute substantially to the prosperous future of molecular electronics and gives me the freedom to conduct this research in the group of my choice.
(80 words)

4.6 Current work experience (if applicable)

Since the beginning of September I started my full time master research under supervison of Dr. Bert de Boer in the group Molecular Electronics headed by Prof. Dr. Ir. Paul Blom on the subject of incorporating conjugated molecules in large-area molecular junctions in order to study tunnel barrier heights and widths for the implementation in a MIMIM transistor. I already mastered the cleanroom course and the basic processing techniques like vapour-evaporation, photolithography, spin coating, plasma etching, reactive ion etching, making SAMs, and making the large-area diode (MIM). Furthermore, I characterized the molecular tunnel junctions electrically by I–V and impedance measurements.

4.7 Previous relevant work experience (if applicable)

-As part of my TopMaster studies, I wrote a review article entitled: "Tunneling hot carrier transistors" (May-June 2007)
-Oral presentation on the Nanoscience symposium 2007, 'Aiming at life' entitled "Virus nanowires", available from www.nanosymposium.net (June 2007)
-Bachelor research project: molecular electronics, April-July 2006, full time.

4.8 International activities (if applicable)

-I am participating in an international Master education. Intensive, daily collaboration with students from 5 different countries for a year long.

4.9 Other academic activities (if applicable)

2007
-Organised Nanosymposium 2007 entitled: "Aiming at life", responsible for funding and general end-responsibility (see www.nanosymposium.net)
-Member curriculum committee TopMaster Nanoscience from January 2007
-Member appointment advisory committee research group Molecular microscopy and spectroscopy in the Zernike Institute of Advanced Materials, from September 2007
-Chairman board Music instrument fund Groningen, from September 2007
-Travel committee Student Orchestra Mira, responsible for funding
-Financial supervision committee Student Orchestra Mira

2006
-Travel committee Student Orchestra Mira concert tour in Switzerland, responsible for funding.
-Financial supervision committee Student Orchestra Mira
-Yearbook committee Student Orchestra Mira

2005
-Organisation RuG Gala concert. Cooperation of Mira, Gica and Bragi to play a grand concert in De Oosterpoort in honour of the 78th University of Groningen lustrum.
-Financial supervision committee Student Orchestra Mira
-Yearbook committee Student Orchestra Mira

2004
-Board student orchestra Mira as treasurer (www.gsomira.nl)

4.10 Research grants and prizes (if applicable)

-Zernike Institute for Advanced Materials: TopMaster Nanoscience scholarship.
Each student is specially chosen during a stringent selection procedure to participate in this honours program and is awarded a scholarship. Dutch students receive 190 euros a month.

4.11 Gaps / other relevant information (if applicable)

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4.12 List of publications (if applicable)

-H.B. Akkerman et al., "Electronic transport through insulating and conjugated molecules", to be submitted in December 2007. My contribution to this article is measurement of several alkane(di)thiols in large area molecular junctions.
-As part of my Master studies, I wrote a review article entitled: "Tunneling hot carrier transistors" (still under embargo)

Statement

I hereby declare that the present form has been completed truthfully

Place: *Groningen*

Date: *19 October 2007*

Signature of applicant:

Goossens

Signature of university representative: