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RF-MEMS Activities in Europe

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Abstract

This paper presents a review of radio frequency microelectromechanical systems (RF MEMS) research within Europe. A tour of Europe is given, identifying the key institutions within France, Germany, Belgium, Switzerland, Sweden and the UK. Some of the activities from these institutions have been mentioned, with corresponding references cited. The European Union's Network of Excellence in RF MEMS and RF Microsystems, called AMICOM, is introduced. Finally, four RF MEMS research projects being undertaken at Imperial College London are briefly discussed. It will be seen that Europe has a very vibrant and healthy activity in RF MEMS research and this is expected to continue for the foreseeable future.

1. Introduction

This paper presents a review of radio frequency microelectromechanical systems (RF MEMS) research within Europe. At this point, it is useful to first defining some common nomenclature associated with RF MEMS, in order to avoid confusion. The term *microsystems technology* is generally used within Europe and this represents specific types of micromachined components (e.g. self-assembled, acoustic-based and micromechanical), true MEMS devices (actuated using electrostatic, piezoelectric, magnetic or electrothermal mechanisms) and microfluidic technologies. In the US and Asia, the term *MEMS* loosely represents microsystems technologies and, thus, includes non true MEMS technologies. In the context of RF MEMS, *RF* refers to radio frequencies beyond DC to sub-millimetre wavelengths. This distinguishes itself from optical MEMS technologies that encompass the mid-infrared to ultra-violet part of the frequency spectrum. With RF MEMS technology, lumped-element and distributed-element transmission line components are generally used. This does not, however, exclude the possibilities of implementing some of the quasi-optical techniques that are employed in optical MEMS. More information on RF MEMS technology, from the perspective of its enabling technologies (e.g. fabrication, RF micromachined components and actuation mechanisms) can be found in the open literature [1].

Because space is limited, micromachined transmission lines, self-assembled structures (e.g. inductors and antennas), thin **f**ilm **b**ulk **a**coustic wave **r**esonators (FBAR) components and all associated resonators, impedance matching networks and filters will not be considered further. Instead, this review paper will only discuss true RF MEMS technologies. Moreover, since the level of activity across Europe is so high, only a basic overview can be given here.

2. RF MEMS Tour of Europe

2.1 France

RF MEMS technology within France has drawn attention from researchers in both public research institutes and private MEMS-related companies. Leading research institutes include CNRS (with the LAAS, IEMN and IRCOM laboratories), CAE-LETI and ENSEEIHT. There are collaborations between these institutes and also with companies, such as STMicroelectonics (France), MEMSCAP and Epsilon.

For example, collaborative research between STMicroelectronics and CAE-LETI was undertaken for realizing thermo-electrostatic RF MEMS switches, as illustrated in Fig. 1 [2]. The switch and its IC driver were all integrated onto a standard

0.25 µm BiCMOS wafer. The design takes advantages of both thermal and electrostatic actuation principles. A DC current is applied to two symmetric heating resistors to deflect the beam. Once the ON state is established, a voltage is applied to capacitors, embedded between the beam and RF ground plane to hold the ON state.

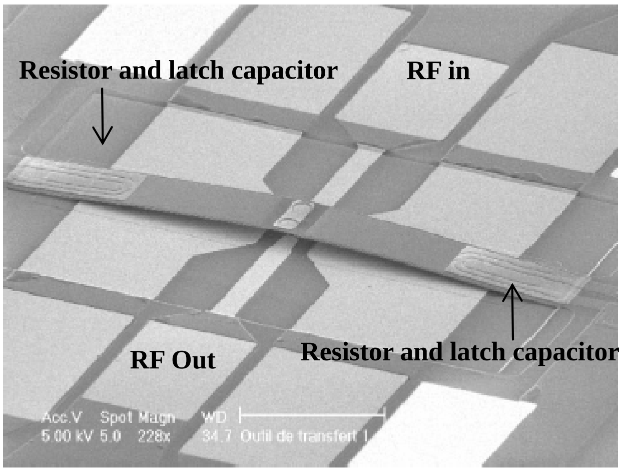


Fig. 1. Thermo-electrostatic MEMS switch [2].

The rapid growth in telecommunication systems dictates advanced RF MEMS devices, in term of sizes and performances. This concern led to the introduction of "new materials" [3]. Aluminium oxide and amorphous carbon thin films were deposited by using pulsed laser deposition (PLD). The electrical and mechanical properties of both materials were characterized. Their potential benefits allow for their use as dielectric and structural materials. Two examples of RF MEMS electrostatic switches were realized from collaboration between SPCTS, IRCOM and LTDS [3].

There are other reported RF MEMS devices from France; mainly switches and their applications. These switches are, for example, purely thermal actuated [4], electrostatic seesaw type switches [5], ohmic shunt switches [6] and shunt capacitive single-pole double-throw switches [7]. Microsystems employing switches were also reported. These included interdigital second-order filters [8], distributed tunable filters [9], tuneable bandpass filters [10, 11]. Tunable microinductors were also realized, whereby the magnetic coupling coefficient between two inductors is changed [12]. In addition, there is much ongoing RF MEMS research, ranging from electromagnetic modelling [13, 14], proposed design methodologies for power switches [15], dielectric reliability [16], RF power handling on tuneable capacitors [17, 18] and reliability modelling [19-21].

2.2 Germany

Unlike other countries, companies within Germany have played an important role in developing RF MEMS. Such companies are DaimlerChrysler, IMST GmbH and Robert Bosch GmbH. Collaborations between companies and universities are also common. For instance, a collaboration to develop toggle switches has been established. First, the mechanical and electromagnetic simulations were presented, along with numerical transient responses [22, 23]. The fabrication details and measured results for single-pole double-throw operation were then reported [24, 25]. Finally, the circuit design for miniature single-pole multiple-throw switches was proposed [26].

A number of MEMS applications have been reported, e.g. a wideband single-pole three-throw switch [27] and a 1-bit digital phase shifter [28]. In particular, automobile-related RF MEMS devices were demonstrated, as illustrated in Fig. 2 [29-31]. Here, single-pole multiple-throw switches and phase shifter subsystems are implemented into phased–array antennas for automotive radar front ends.

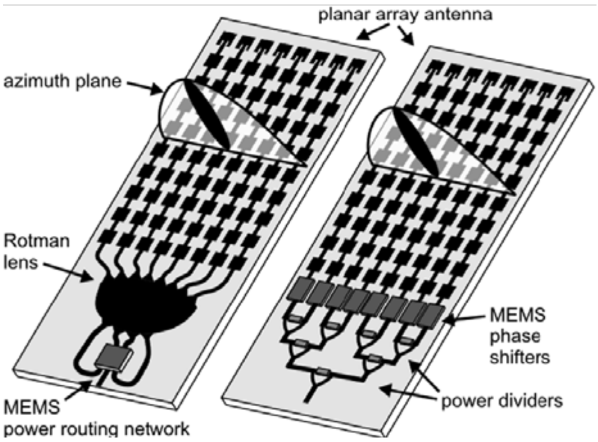
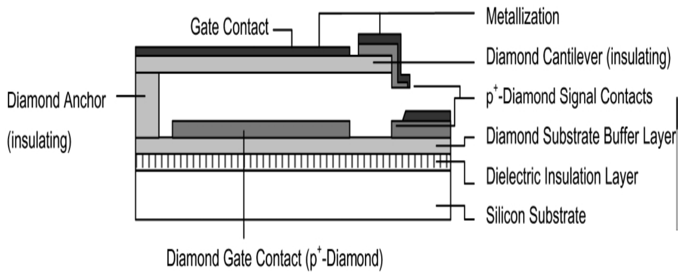


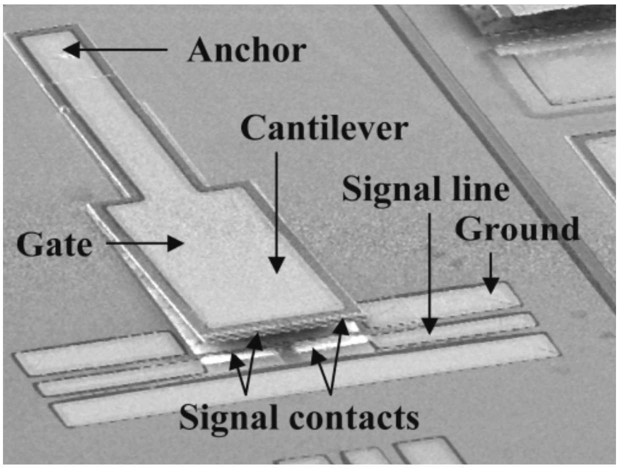
Fig. 2. Concepts for beam steering and prototype of RF MEMS antenna front ends [31].

Also, novel switch concepts have been presented. For example, the double anchor switches [32] and serial ohmic and capacitive switches [33]. The former was design to circumvent the self-actuation problem, by having top and bottom drive electrodes. As a result, the switch can be operated in a single-pole double-throw mode, as it can switch between the membrane (input) to either of the drive electrodes (outputs 1 and 2). With the latter, a serial combination of toggle ohmic contact switch and shunt air-bridge capacitive membrane switch was realized in order to achieve high bandwidth and high power RF operation.

There is also other RF MEMS related research within Germany, such as the numerical analysis of capacitive switches [34], dielectric impact on reliability [35] and CMOS-compatible fabrication concepts [36]. Moreover, the novel exploitation of synthetic diamond in RF MEMS has been proposed [37, 38], as shown in Fig. 3. The motivation in designing CVD-diamond cantilevers for RF switches was drawn from its excellent static and dynamic properties, e.g. efficient heat removal, high temperature and mechanical stability. As a result, high power applications are seen as the main driver for this technology.



(a)



(b)

Fig. 3. Diamond-structured RF MEMS switch; (a) schematic cross section and (b) SEM micrograph [37].

2.3 Belgium

Various areas of RF MEMS research are being conducted in Belgium, with IMEC and Katholieke Universiteit Leuven being the principal institutes. Similar to other countries, the switch is the main focus. Novel series capacitive switches were realized [39, 40]. Due to its configuration, as illustrated in Fig. 4, the insertion loss and isolation properties can be separately optimized and the capacitance ratio can be greatly increased. An RF MEMS filter-through device, employing this switch, requires a simpler biasing scheme than the conventional combination of series and shunt switches for broadband applications.

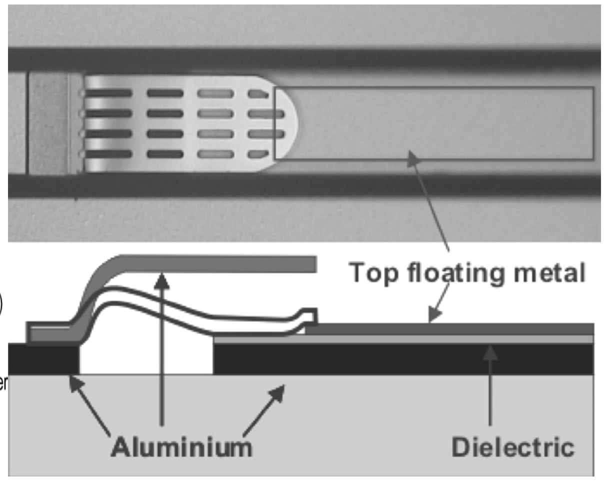


Fig. 4. Microphotograph and schematic of series capacitive switch [40].

As one of the major reliability issues, stiction (due to dielectric charging effects) has been investigated in detail [41-45]. In addition, self-actuation phenomena, for both cantilever and suspension bridge structures, have been qualitatively studied and modelled [46-47]. The study was extended to analyze the RF power handling capabilities of switches. The more practical situation was considered, which is when there is impedance mismatch between the switch in its ON state and the associated network [48]. Furthermore, in terms of reliability, the mechanical shock and vibration can affect the insertion loss of RF MEMS devices. To a degree, these effects can be reduced by increasing the stiffness of suspended structures. A numerical analysis method was introduced for determining the required stiffness [49].

Research into the packaging RF MEMS devices has also been extensively carried out in Belgium. The effect of 0-level to 2-level packaging on the RF performance has been investigated [50, 51]. Here, a new sealant material was developed using BenzoCycloButene (BCB) [52-54].

2.4 Switzerland

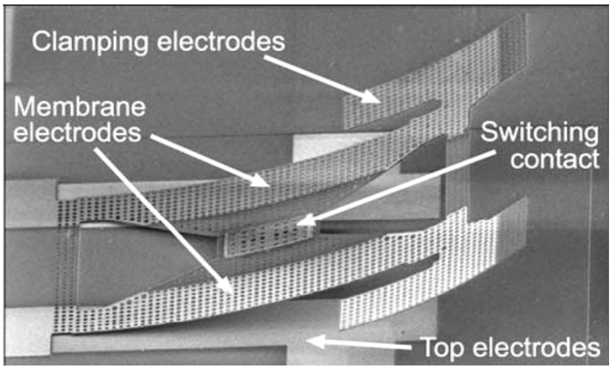
A new concept for using a ferroelectric material, called FeMEMS, was introduced in Switzerland by the Swiss Federal Institute of Technology Lausanne [55]. A layer of this material was deposited between electrodes, to act as a variable capacitor or switch, in place of a dielectric. The resulting devices can take advantage from the hysteresis property, e.g. the capacitance value can be memorized without an applied potential.

There is another interesting piece of RF MEMS research going on in Switzerland; the MEMS suspended-gate MOSFET [56, 57]. This device consists of a metal membrane on a MOS transistor. It was fabricated on an SOI substrate that is suitable for high frequencies, due to its low loss sapphire substrate.

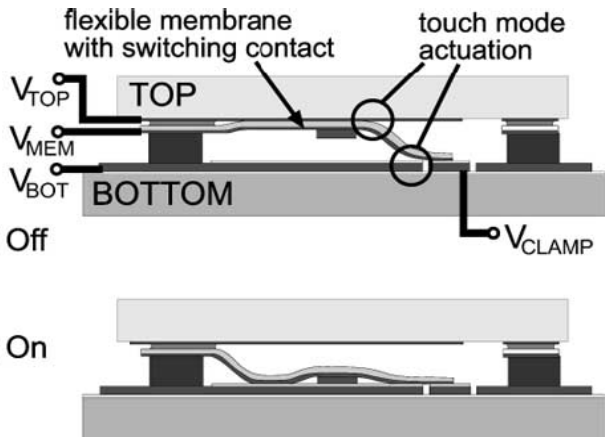
A new fabrication technique, employing amorphous silicon, was also introduced [58]. This Silicon Sacrificial Layer Dry Etching (SSLDE) technique involves the sputtering or LPCVD deposition of silicon as a sacrificial material. It is then removed by plasma etching. The process is not only reliable but also capable of fast and high selectivity etching [58].

2.5 Sweden

An S-shaped electrostatic series switch was realized by the Royal Institute of Technology, Stockholm [59, 60]. The switch configuration employs a double-electrode scheme. As illustrated in Fig. 5, a voltage is applied between the membrane and the bottom electrode, to close the switch, and between the membrane and the top electrode, to open the switch. The switch obtains high isolation in the OFF state, due to large separation between electrodes. With the active-opening arrangement, the restoring force within the beam can be omitted. Consequently, the beam is very thin, leading to a reduction in actuation voltage. Moreover, the switch benefits from a lower risk of stiction and, hence, is more reliable.



(a)



(b)

Fig. 5 (a) Out-of-plane bending thin membrane after releasing and (b) actuation mechanism [59].

2.6 UK

A number of universities and companies within the UK are developing RF MEMS technologies. The main UK university activity is undertaken at Imperial College London, with research also being carried out at Cranfield University, Heriot-Watt University and the University of Glasgow. The main UK companies developing RF MEMS products are Microsaic Systems Ltd. and QinetiQ. Some of the activities at Imperial College London, and its spin-out company Microsaic Systems Ltd., will be mentioned in Section 4.

Electromagnetic modelling of high power switches has been reported by Heriot-Watt University [61-63]. Also, dielectric materials development is being carried out at the University of Glasgow. Here, the use of ultra-thin CVD Si_3N_4 films has been demonstrated to have an increase in capacitance per unit area and breakdown electric field [64]. In addition, collaborative research between Cranfield and Imperial [65] and also Cranfield and Nottingham is underway in the area of piezoelectric materials [66].

2.7 Other countries in Europe

A wide variety of RF MEMS development has also been reported from other European countries, e.g. Finland, Italy, The Netherlands, Spain and Turkey. This research ranges from mechanical and electromagnetic modelling, new architecture design and circuit integration. For example, gas damping [67, 68], intermodulation distortion [69] and lump element models [70] have all been investigated. A temperature insensitive RF MEMS capacitor was recently reported [71]. RF MEMS switches mainly rely on electrostatic actuation, however, developments in thermally-actuated buckle beam switches have also been demonstrated [72]. Additionally, there have been demonstrations of RF MEMS applications, such as RF power sensing [73, 74], matching networks [75], phase shifters [76] and reconfigurable microstrip antennas [77].

Broad based collaborations between European countries can also be seen. For example, an RF SiGe MEMS consortium exists between France, Germany and Sweden [78]. In addition, extensive research in RF MEMS tuneable capacitors [79, 80] and switches [81, 82] are being carried out between The Netherlands and Belgium.

3. The AMICOM Network of Excellence

Under the European's Union's Framework VI programme, a fully-funded Network of Excellence (NoE) in RF MEMS and RF Microsystems was created. Called **A**dvanced **M**EMS for RF and M**i**llimeter Wave **Com**munications (AMICOM), this 3-year NoE was officially launched on 1st Jan. 2004, but has enough momentum to continue well after 2006. AMICOM is made up of a virtual network of 25 research institutes, across 14 countries, all working in RF MEMS technologies. A list of the partner institutions is given in Table 1. Within these partners, more than 120 active professionals are participating in joint research projects, summer schools and conferences.

AMICOM members are dedicated to the development of RF MEMS and the combination of advanced integrated circuits and packaging technologies to form RF microsystems. With regular meetings, the network aims to achieve a leading role in international research in RF MEMS through the; (i) joint use of shared knowledge (with the use of its own interactive web site, http://www.amicom.info/) and physical resources (with the exchange of researchers); (ii) joint work packages and though North Star Projects; and (iii) joint activities to educate and exchange knowledge on RF MEMS and RF microsystems.

For the second half of this NoE, three North Star Projects (NSPs) have been created, that aim to focus the combined resources of AMICOM in order to realize significant working demonstrators. These project are called: **R**eflect **A**rrays and **R**econfigurable **P**rinted **A**ntennas (RARPA); **Re**configurable **Ra**dio **F**ront-**E**nd (ReRaFE) and **M**illi**m**eter Wave **Id**entification (MMID).

Also, the popular 1-week Summer Schools are hosted in Crete (Greece) in 2004; Sinaia (Romania) in 2005; and London (UK) in 2006. The Summer School are open to non-member institutions and companies (from anywhere in the world).

4. RF MEMS at Imperial College London

The Optical and Semiconductor Devices Group, within the Department of Electrical and Electronic Engineering at Imperial College London, is the leading RF MEMS University research group within the UK and one of the largest in Europe. In this section, just four RF MEMS projects are introduced.

4.1 Single-pole multiple-throw rotary switch

A novel single-pole eight-throw rotary switch has been recently designed, fabricated and tested. The configuration is based on the electrostatic wobble motor [83-85]. It consists of two components: stator and rotor. In the wobble motor, the centre of the rotor is raised above the stator and is attracted downward, due to the electrostatic potential applied to the stator pole underneath. For RF switching, the stator is modified by incorporating one input and eight output CPW transmission lines around the perimeter of the rotor contacts [86-87].

4.2 Laterally actuated, low voltage switch

Imperial College London, with its spin-out company Microsaic Systems Ltd., and the space technology company EADS-Astrium Ltd., have been working together on RF MEMS application for space. As the complexity in space communication systems increases, the requirements of switching become increasingly demanding. An electro-thermal actuated switch was developed specifically for satellite based communications (e.g. low control voltage, vibration and shock resistance). In particular, the switch was realized in a 3-port, single-pole double-throw arrangement [88-89].

Although the switch requires power consumption during the electro-thermal switching operation, a latching configuration is employed to allow for zero hold power in either switch state. Unlike most vertical MEMS switches, the actuation is lateral, which can provide high open state isolation. The use of thin-film microstrip (TFMS) was employed to keep the device compact.

4.3 Filters

In collaboration with Mitsubishi Electric Co. (Kamakura, Japan), a novel millimetre-wave RF MEMS filters are currently being investigated that employs distributed-element components to reduce the effects of parasitics and minimise insertion loss. Traditional coupled-line filters are very popular for applications having fractional bandwidths below around 15%. While these filters are highly sensitive to non-ideal material/fabrication tolerances, it is this feature that is being exploited within the novel filter design proposed here. All the resonators and interconnecting transmission lines are implemented using miniature air microstrip lines, in order to maximise the Q-factors for this monolithic implementation. This approach can create resonators that have double cantilevers; which facilitates electrostatically-actuated tuning of the coupled lines.

4.4 *MaSPrint*

RF MEMS technology is poised to step out of research laboratories and into commercial foundries for large volume manufacturing. Traditional microfabrication technologies, e.g. surface and bulk micromachining, have long been employed to manufacture RF MEMS. These technologies allows for the definition and processing at the (sub-)micron-scale. One of the main drawbacks of this kind of microfabrication is the relatively high costs associated with this technology. However, screen-printing has seen major breakthroughs, through the development of photoimageable pastes and ultra-fine screen meshes. By applying conventional microfabrication techniques to screen printing, an entirely new manufacturing technology emerges. This **M**icrom**a**chined **S**creen **Print**ing (*MaSPrint*) technology not only fulfils a fabrication technology gap but also offers new prospects in fast, cheap and simple RF MEMS manufacturing [90].

With the need for a sacrificial layer, for releasing suspended structures, a suitable paste has had to be identified [90]. While this technology is still in its early development, a simple suspension bridge has been demonstrated, as shown in Fig. 6. A more advanced *MaSPrint* technology has also been proposed, with the use of latent images in photopolymer materials. A wide range of micromachined and MEMS devices have been identified as suitable demonstrators for this technology, such as miniature air-microstrip lines, uniplanar filters, RF MEMS switches, variable capacitors, high performance filters and phase shifters [90].

Fig. 6. Silver suspension bridges, fabricated using basic *MaSPrint* processing [90].

5. Conclusions

This paper has presented a detailed review of true RF MEMS research within Europe. A tour of Europe has been given, identifying the key institutions within France, Germany, Belgium, Switzerland, Sweden and the UK. Some of the activities from these institutions have been mentioned, with corresponding references cited. The European Union's Network of Excellence in RF MEMS and RF Microsystems, called AMICOM, was introduced. Finally, four RF MEMS research projects being undertaken at Imperial College London have been briefly introduced. It will be seen that Europe has a very vibrant and healthy activity in RF MEMS research and this is expected to continue for the foreseeable future.

Table 1 List of AMICOM partner institutions

Country	Institute	Internet homepage
Belgium	Interuniversity MicroElectronics Center (IMEC)	http://www.imec.be
	Katholieke Universiteit Leuven (TELEMIC)	http://www.kuleuven.ac.be
Finland	VTT Technical Research Center of Finland (VTT)	http://www.vtt.fi
France	Centre National De la Recherche Scientifique (CNRS)	http://www.cnrs.fr
	ARMINES	http://www.armines.net
	CEA-LETI	http://www-leti.cea.fr
Germany	Darmstadt University of Techology (TUD)	http://www.tu-darmstadt.de
	Technical Institute of München (TUM)	http://www.hft.ei.tum.de
	University of Ulm (ULM)	http://www.uni-ulm.de
	The Fraunhofer-Gesellschaft (FHG)	http://www.fraunhofer.de
Greece	Foundation for Research &Technology Hellas (FORTH)	http://www.forth.gr
	Technological Educational Institute of Crete (TEI_C)	http://www.teiher.gr
	University of Athens	http://www.uoa.gr
Israel	Israel Institute of Technology (Technion)	http://www.technion.ac.il
Italy	University of Perugia	http://www.diei.unipg.it
	Trentino Cultural Institute (ITC-IRST)	http://www.itc.it
The Netherlands	Delft University of Technology	http://www.tudelft.nl
Poland	Institute of Electronic Materials Technology (ITME)	http://www.itme.edu.pl
Romania	National Institute of Research and Development in Microtechnologies (IMT)	http://www.imt.ro
Sweden	Chalmers University of Technology	http://www.chalmers.se
	University of Uppsala	http://www.uu.se
Switzerland	Swiss Federal Institute of Technology (EPFL)	http://www.legwww.edfl.ch
Turkey	Middle East Technical University	http://www.metu.edu.tr
UK	Imperial College London	http://www.ee.imperial.ac.uk
	Cranfield University	http://www.nanotek.org

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