A Nordic approach to novel micro- and nanotechnology

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Abstract

An overview of micro- and nanotechnologies at VTT Technical Research Centre of Finland is presented. Novel research is carried out at several areas. Related to micro- and nanoelectronics, an efficient way for manufacturing nanoscale components using nanopattering as well as superconductor-semiconductor-superconductor (S-Sm-S) microcooler is presented. MEMS activities include development of a high quality 13 MHz reference oscillator and integrated CMOS and MEMS circuits for pressure sensing. Micromodules and structures based LTCC are described. At microwaves and millimetre waves, impedance tuners and matching networks for 4 to 100 GHz are depict. Summary on roll-to-roll printed electronics for making organic light emitting diodes (OLED), diffractive ROM memories and other components is given.

1. INTRODUCTION

Micro- and nanotechnology is one of the key focus areas of VTT Technical Research Centre of Finland. Micro- and nanotechnology research at VTT is divided into five main areas as follows: 1) Micro- and nanoelectronics, 2) MEMS and micropackaging technologies, 3) LTCC based micromodules, 4) microwave and millimeter wave technology, and 5) printable electronics and optics.

2. MICRO- AND NANOELECTRONICS

Step & Stamp Nanoimprinting Lithography

The capability to produce sub-50 nm features using nanoimprinting lithography was demonstrated already 1995 by Chou [1]. The field became rather active by the end of 90's and most the groups concentrated on development of large area parallel process. Micro and Nanoelectronics Centre has been developing nanoimprinting technique actively since 1997.The new idea then was to mimic the operation of an optical stepper and develop a sequential process for nanoimprinting [2]. The process is schematically shown on the left in Fig. 1. A heated stamp is pressed into a polymer film. The pattern on the stamp is transferred into the polymer. Next, the stamp is cooled down below the glass transition temperature of the polymer and lifted. The sequence is then repeated. We have demonstrated sub-10 nm features using silicon stamps as shown on the right in Fig. 1.

Currently VTT is coordinating a European Commission funded integrated project Emerging Nanopatterning Methods (NaPa) with 35 groups from 14 countries [3]. One of the outcome from the project is the NPS300 nanostepper capable for hot embossing and UV nanoimprinting. The prototype tool has been recently installed in the clean room of Espoosite.

Silicon-on-Insulator Devices

Micro and Nanoelectronics Centre is also actively investigating ultrathin silicon-on-insulator (SOI) structures and devices. These include single and dual gate MOSFETs with channel thickness down to 8 nm [4, 5], investigation of single electron effects [6] and confined acoustic phonons [7]. One interesting application for SOI material is superconductor-semiconductor-superconductor (S-Sm-S) microcooler [8]. Operation of a S-Sm-S cooler is depicted in Fig. 2. At small bias ($V < 2\Delta/e$) only the most energetic electrons in the thermal tail of the Fermi distribution can tunnel from the semiconductor through the left Schottky junction into the superconductor. Similarly the quasiparticles below the energy gap in the right superconductor can tunnel into the semiconductor. This reduces the total energy of the electron gas and leads to the cooling effect. Small S-Sm junctions can also be used to measure non-invasively the electron temperature.

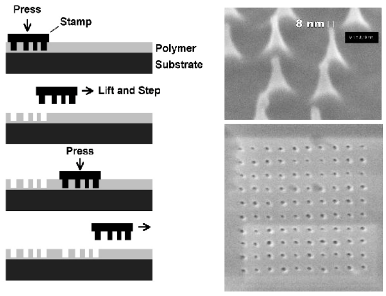
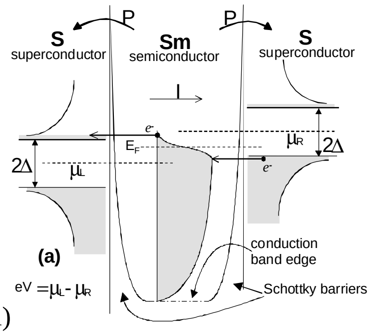
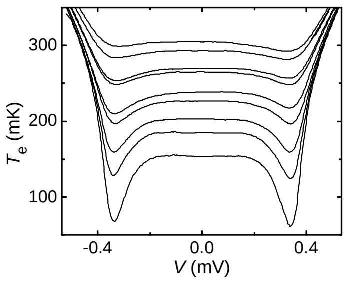


Fig. 1. On the left, step & Stamp imprint lithography process shown schematically. On the right, SEM images of a silicon stamp with 100 nm high pillars and sub-10 nm diameter and an imprint made with the stamp. The stamp was fabricated using e-beam lithography and standard silicon processing.



a)



b)

Fig. 2. a) Energy band diagram of an S-Sm-S coole, b) measured electron temperature T_e at different bath temperatures as a function of junction bias voltage.

The experiments were performed on a 50 ... 70 nm-thick oxidized SOI films with high n-type doping. A 300 nm-thick Al film acted as superconductor. On the right in Fig. 2 is shown measured electron temperature in the SOI film as a function of the voltage across the S-Sm-S cooler at different substrate temperatures. Two clear minima can be seen in all the curves at bias slightly below twice the superconducting gap of the aluminum film ($2\Delta/e \approx 0.40$ mV). The relatively large decrease in electron temperature is due to the large thermal resistance between the electrons and the lattice (phonons). In addition, a model for the energy flow between electrons and phonons in many valley semiconductors, such as silicon, has been developed [9].

3. MEMS AND MICROPACKAGING TECHNOLOGIES

VTT has taken three different technological approaches for Microelectromechanical systems (MEMS) fabrication: polysilicon, amorphous metal, and SOI micromachining. Each of them suit for different applications. The former two make use of thin-film technology while the third one is based on single crystal silicon. With polysilicon technology, devices such as Fabry-Perot interferometers, thermopiles, and pressure sensors are made on a commercial basis. Amorphous metal micromachining is a low thermal budget cycle, being good for RF-MEMS and microphone fabrication. SOI technology is mostly used for resonator studies as well as monolithic MEMS-CMOS integration. Narrow-gap technologies are in our special focus.

MEMS technology has several features, which make them particularly suitable for space applications. MEMS devices are small and their power consumption is low. The operation of several MEMS devices relies on mechanical properties of silicon structures, which are rather insensitive to radiation effects. VTT has already developed MEMS-based instruments for space applications [10, 11] but there are still several new applications to be addressed.

Miniaturized and accurate electronic compasses and magnetometers are needed in navigation and in mapping magnetic fields. Existing magnetoresistive sensors suffer from high power consumption and insufficient stability. VTT has developed a unique MEMS compass whose power consumption is reduced by using capacitive readout techniques. Measurement of the three vector components of the magnetic field can be integrated on a single chip leading to a highly miniaturized device.

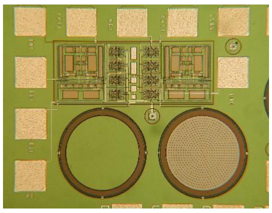
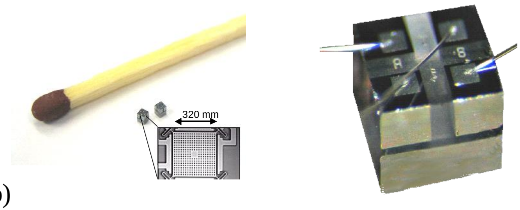
a)  b) 

Fig. 3. a) Monolithic pressures sensor, patented by VTT, contains both the pressure-sensing flexible membrane as well as the readout electronics [12]. b) MEMS resonators, with low-pressure wafer-level packaging, have been developed for a 13 MHz reference oscillator with a high stability and a low phase noise.

Pressure sensors, shown in Fig. 3a), are useful in monitoring environmental parameters in several planetary missions. VTT has developed a range of manufacturing solutions for producing various pressure sensors depending on the measurement range and packaging strategy. Stable, high-resolution readout electronics, with a resolution better than 1 ppm (parts per million) of the full measuring range, has been demonstrated. Novel coating and packaging techniques have been developed to use MEMS pressure sensors in hostile environments.

MEMS gravimeters have been identified as useful sensor for several studies of extraterrestrial objects. Also in these applications, the stability and the resolution of the devices are critical. VTT has invented special solutions to increase the electromechanical stability of such devices. VTT has also developed packaging techniques for MEMS devices that do not deteriorate the ideal mechanical properties of single-crystalline silicon sensing elements.

MEMS technology can be used to improve the radio telemetry systems in terms of physical size and power consumption. VTT has developed small, stable, low power MEMS resonators that can be used to replace quartz crystal resonators in reference oscillators, see Fig. 3b). In RF front ends, MEMS components can be used for filters, tunable tank circuits, and Rx/Tx switches. With appropriate integration technology, highly miniaturized radios working at low power levels can be realized [13].

4. MICROMODULES BASED ON LTCC

A multilayer ceramic platform based on low temperature co-fired ceramics (LTCC) technology provides a fruitful platform for heterogeneous integration. The fabrication of a multilayer ceramic substrate by the use of LTCC technology begins from glass ceramic sheets that are blanked and punched in order to form via holes. Secondly, via holes are metallized to form electrical interconnects between layers. The next step is the patterning of electrical conductors and passive circuits onto each layer by the use of screen-printing or photo imaging. Layers are laminated and fired at temperatures below 980 °C temperatures. Final circuits are separated by dicing. The relatively low sintering temperatures of LTCC materials allow the use of high conductivity metallization, such as, silver and gold for conductors. At the end, the SOP module is finished by assembling discrete devices onto the substrate.

Precision Structures

For photonics and sensor applications, the ability to create 3D precision structures on the LTCC substrate is a very important feature. Open cavities can be made on the surfaces of the LTCC substrate for the mounting of discrete semiconductor devices. U-grooves can be processed by punching and photolithographic processes on the substrates. Optical fibers can be easily attached to the grooves, see Fig. 4. Buried cavities or channels can be manufactured for liquid or gas flow in cooling or analyzing applications, Fig. 4. Accurate through hole structures are useful for photonic packaging. Standard cavities are manufactured by punching a window to the tape layers, which are then laminated together and co-fired. An example of a through hole grid in an LTCC substrate is shown in Fig. 4. Typically, the dimensional tolerance for a medium sized cavity, 5 mm x 5 mm x 1 mm, for example, is +/- 20 μm in all three axes. The most accurate through hole structure, however, is made by punching the hole after laminating the tape layers together, thus eliminating the layer-to-layer misalignment. The diameter of a through hole can be controlled to ±3 μm tolerance for hole diameter range of 0.1…1 mm. The minimum hole pitch is typically 2 times the diameter of the hole.

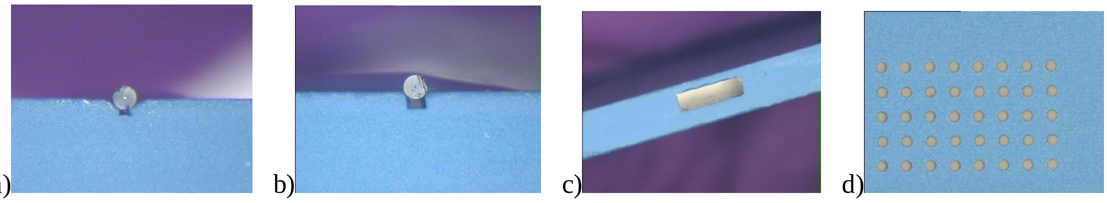
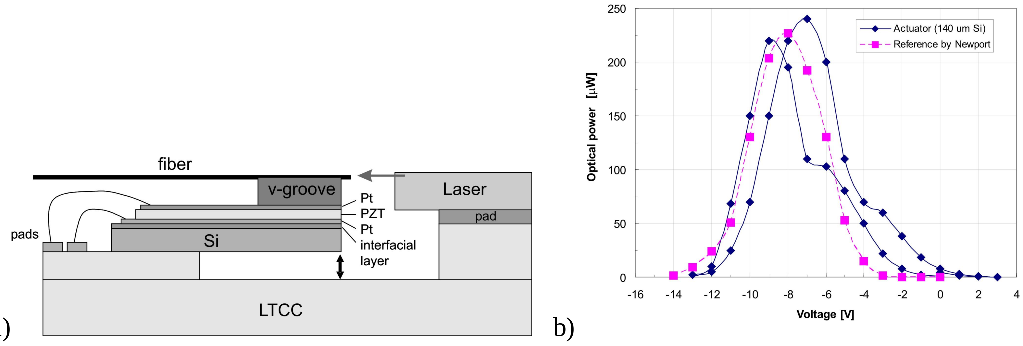

a) b) c) d)

Fig. 4. a) Fiber attached on a punched groove, b) photoimaged groove, c) integrated channel cross-section 1.4 mm x 0.4 mm, d) grid of holes through 0.6 mm thick substrate (hole diameter 138 μm, hole pitch 300 μm).



a) b)

Fig. 5. a) Schematic representation of a fiber pigtailed laser based on dynamic alignment, b) Optical power coupled into the fiber versus the MEMS driving voltage. The driving voltage is changed from 0 V to -13 V and from -13 V to 3 V and back to 0 V. The reference curve measured by an autoalign station plotted with the dashed line.

Dynamic Device Alignment

In order to align an optical fiber dynamically to maximize optical coupling efficiency, a piezoelectric ceramic thin-film MEMS actuator was designed and fabricated [14]. Silicon was chosen as the flexural substrate of an actuator due to its excellent mechanical properties, and very good material properties for thin-film deposition. Actually, $Si/SiO_2/Ti/Pt/PZT$ is the most widely used sequence of materials for piezoelectric thin-film structures. Actuators with the geometry specified to fit on LTCC platform were fabricated on Si substrates (5 mm wide and 20 mm in length) with thicknesses of 75, 90, and 140 μm. The thickness of PNZT films in Pt/PNZT/Pt capacitor stack was 750 nm, and the active area was 4 mm × 10 mm. According to calculations, actuators with a 140 μm thick substrate would have a displacement value of around 10 μm when operating at 10 V, whereas an actuator with a 75-μm thick substrate would be displaced around 40 μm.

According to the measured graphs shown in Fig. 5, it is feasible to manufacture an optical fiber alignment MEMS, which is able to perform dynamic optical coupling efficiency adjustments. Even a 10-μm movement, generated by an actuator based on a 140-μm substrate at the voltage of -10 V, was enough to align a single-mode optical fiber in order to maximize the optical coupling efficiency between the laser and fiber.

Band-pass Filter

A 3-pole band-pass filter [15] structure designed and characterized by IRCOM and fabricated at by VTT is shown in Fig. 6a). The filter was based on a resonator structure, which was realised by a periodic lattice of metallised via holes. According to Fig. 6b), the measured insertion and reflection losses of the filter with 7 % -3 dB bandwidth centered at 38 GHz are small and in good agreement with simulations.

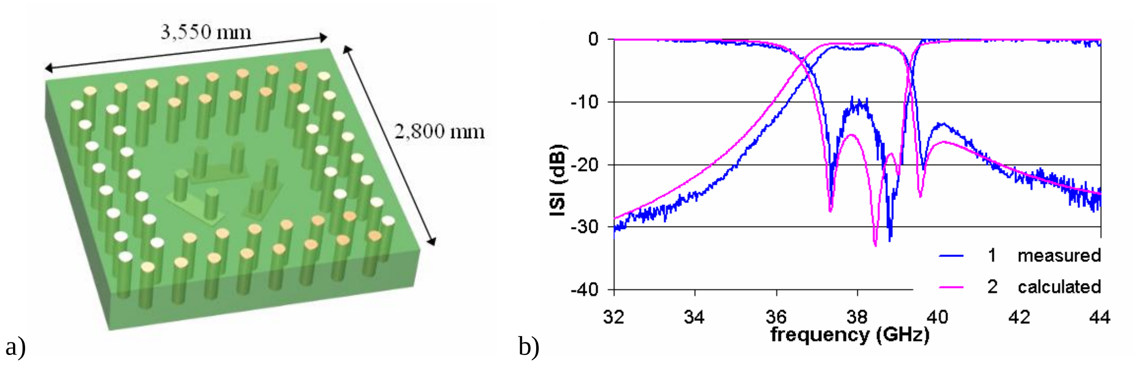


Fig. 6. a) Schematics of optimised 3-pole filter, b) Simulated (dashed) and measured insertion and reflection losses.

5. MICROWAVE AND MILLIMETER WAVE TECHNOLOGY

MEMS technologies have been applied to several types of microwave and millimeter wave components and circuits as well as systems at VTT. Fig. 7 shows schematically traditional multi-band front-end and its reconfigurable counterpart [16]. The figure summarizes at least partly VTT's focus on microwave and millimeter wave microtechnologies, which has been mostly in tunable, switchable, and reconfigurable components circuits with new functionalities. These include MEMS based switches, varactors [17], power sensors [18], phase shifters [17], reconfigurable matching networks and impedance tuners [19, 20, 21]. Application areas for these are, for example, wideband power sensing applications, reconfigurable antennas and amplifiers, phased array antennas, and multi-band systems.

Reconfigurable impedance tuners and matching networks are beneficial in antenna and amplifier applications. For example in multi-band and multi-standard systems, both DC power consumption and RF power loss can be minimized by using reconfigurable matching networks. We have developed matching networks for 4 ... 20 GHz and 20 ... 50 GHz multi-band systems. In addition, we have developed MEMS based impedance tuners for instrumentation and measurement applications to further improve measurement automation and accuracy in on-wafer measurements. Several integrated impedance tuners have been realized to cover 6 ... 120 GHz frequency range. The tuners are based on stub topologies, and electrical impedance tuning is done with switched MEMS capacitors. The tuners have 10 ... 13 switched capacitors producing 1024 ... 8192 (2^{10}-2^{13}) different impedances. The impedance tuners have large impedance coverage at wide frequency range. They can also generate high reflection coefficients, so that, maximum measured $|\Gamma_{MAX}|$ is 0.99 at 75 GHz (equal to VSWR 199) [21]. Fig. 8 shows photograph of a fabricated 20 ... 50 GHz impedance tuner and its measured impedance coverage at 30 and 40 GHz.

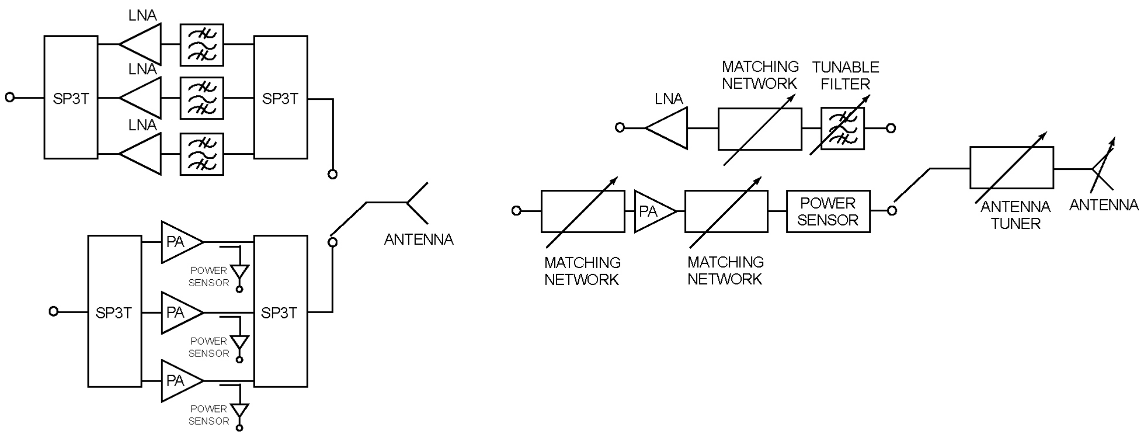


Fig. 7. Conventional (on the left) and reconfigurable multi-band front-end (on the right) [16].

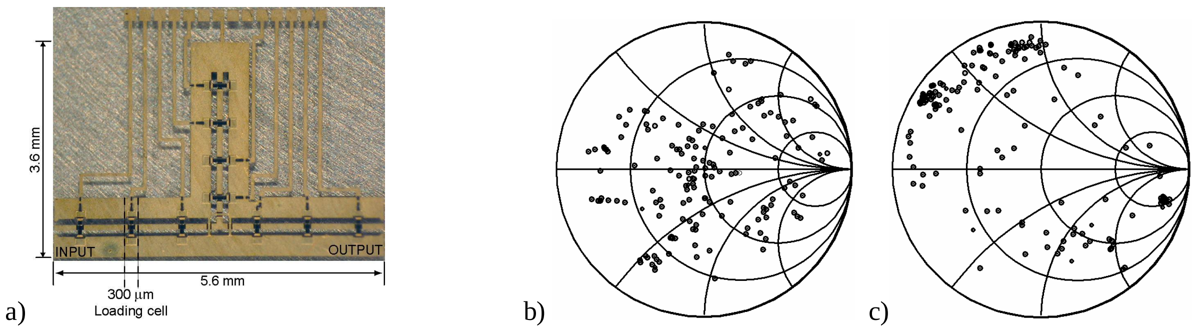


Fig. 8. a) Photograph of a fabricated 20 ... 50 GHz single-stub impedance tuner with 10 MEMS switches. Measured impedance coverage (160 points out of 1024 possible impedances) b) at 30 GHz and c) at 40 GHz [20].

6. PRINTABLE ELECTRONICS AND OPTICS

Conventional and advanced printing methods are well-established techniques and are nowadays routine tools for the packaging and printed matter industry. From the packaging and printing industry point of view, the roll-to-roll (R2R) technique is the only method of choice capable of fulfilling the demanded production volume and integration of the existing production process with a low cost level. Moreover, conventional printing techniques are additive techniques reducing the amount of waste during the fabrication. When simple electrical and optical components can be fabricated using conventional printing techniques, their integration into the low-end products will be possible.

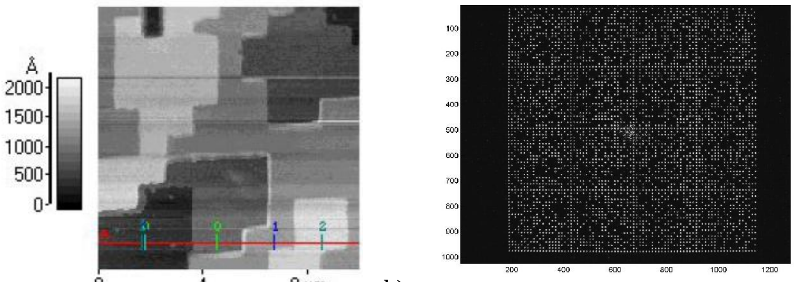
VTT has investigated the possibilities to fabricate different type of electronic, optical and optoelectrical components using conventional roll-to-roll printing technologies, such as, gravure-, off-set-, ink-jet, hot-embossing and flexographic printing. From those techniques, most of the attention was paid to the gravure printing of passive and active electrical, optical and optoelectrical components, whereas diffractive optics have been produced using the roll-to-roll hot-embossing technique. In the following paragraphs, couple of roll-to-roll fabricated demonstrator devices are shown as examples from the capability of these techniques [22].

For the realization of active and intelligent packages, simple electrical components, such as, resistors and conductors are required. For the fabrication of these components, conductive polymers and particulate inks have been used and demonstrated [23]. The main advantage of particulate conductors over polymeric conductors is their higher conductivity levels in comparison to polymeric conductors. The conductivity level of a typical silver-based particulate conductor material suitable for printing purposes is in the scale of 10^3 S/cm.

From the active package point of view, the most critical component is the display element. During our research projects, R2R manufacturing technologies for the organic light emitting diodes (OLED) using the gravure printing of organic layers on commercial ITO-PET substrate was investigated. The R2R fabrication of OLED was started by the gravure printing of modified PEDOT-PSS ink, which enhances the performance of the final device. On top of the PEDOT-PSS layer, emitting polymers or small molecules doped in a suitable host were printed by using the gravure technique. For the fabrication of cathode, the evaporation (Mg-Al) technique was used, even though screen-printed cathodes (Ag) have also been successfully used. In Fig. 9, printed blue-orange OLED behaving as a “temperature indicator” in a medicine package is shown.

Different type of optical elements can be used in packages to produce different types of entertaining or impressive effects. In some cases, the information content of the packages can be also increased by using properly designed and fabricated optical elements. In packages, light guides can be used for decorative purposes. In such cases, light from the integrated light source can be coupled into the light guide, which delivers light to the destination area of the package where it can be coupled out with the desired shape producing shining figures. Three different types of approach to the fabrication of light guides were used: combined technique where embossed grooves on substrate are fulfilled with optical core material, and direct write using gravure or ink-jet techniques. The best results were obtained using the gravure printing technique. The minimum optical attenuation obtained so far is 1.8 dB/cm.

Fig. 9. OLED (blue and orange) -based temperature indicator on active package.



a) b)

Fig. 10. a) Roll-to-toll hot-embossed optical read only memory, b) SEM-picture from roll-to-roll fabricated OROM-element (T. Haring, Univ. Joensuu). Image created by the transmission type of element on CCD camera.

By using roll-to-roll hot-embossed microstructures, it is also possible to generate read-only types of optical memories, which we have also demonstrated. The basic idea of the memory is the use of diffractive microstructure. When the R2R hot-embossed diffractive element is illuminated with a laser, it produces a data matrix pattern containing information in a manner similar to that of a standard bar code but with much higher data density (up to 250 000 bytes/cm^2). The pattern is read with a camera phone and the information is decoded. In this concept, the product package can carry a huge capacity of information itself. In Fig. 10, roll-to-roll hot embossed 4-level element and an image from a transmission type optical read-only memory can be seen. The processed data showed a bit-error-ratio (BER) of 0.2%, including the central peak.

7. CONCLUSIONS

Micro- and nanotechnologies at VTT have been reviewed. Research is carried out in several areas. A summary of presented technology and activities is following:

Micro- and nanoelectronics puts a large emphasis is in the field of imprinting lithography for developing techniques for large area parallel imprinting. We have shown that sequential imprinting method, Step & Stamp Imprint Lithography (SSIL), is applicable for pattern large areas. The SSIL method is a relative flexible patterning method, which can be used for large area imprinting, multi layer imprinting and mixing & matching with UV -lithography. An example with interesting space applications is Normal metal - insulator -superconductor (NIS) tunneling refrigeration that provides a solid state alternative cooling method for 100 mK temperatures. We are investigating the possibility to replace the normal metal in the NIS devices with degenerate silicon. In this approach, no insulating layer is required and the tunneling occurs through a Schottky barrier formed at the semiconductor - superconductor (Sm-S) interface.

In MEMS and micropackaging technologies, we have three different technological approaches for MEMS fabrication: polysilicon, amorphous metal, and SOI micromachining. The former two make use of thin-film technology while the third one is based on single crystal silicon. Each of them suit for different applications. With polysilicon technology, devices, such as, Fabry-Perot interferometers, thermopiles and pressure sensors are made on a commercial basis. Amorphous metal micromachining is a low thermal budget cycle, being good for RF-MEMS and microphone fabrication. SOI technology is mostly used for resonator studies as well as monolithic MEMS-CMOS integration. Narrow-gap technologies are in our special focus.

In system-on-a-package approach (SOP) the aim is to integrate optical and electrical functions in the package. *LTCC based micromodule technology*, enables processing of 3D precision structures, such as, grooves, cavities, holes and alignment fiducials. These are applicable for the passive alignment of photonic devices thus allowing cost reductions in high-volume production. For dynamic alignment purposes, the integration of MEMS actuators into LTCC structure showed out to be feasible. In addition, latest collaboration results on band-pass filters based on a resonator structure, which was realised by a periodic lattice of metallised via holes, are very promising providing novel means for millimeter wave systems.

In microwave and millimeter wave technology, impedance matching circuits based on MEMS technology enabling easily more than one octave operation. The designs are based on the use of capacitive switches in a triple, double, and singe stub configurations as well as in a distributed transmission line design. The use of capacitive switches will enable 2^n number of impedance points (n is number of the switches), which cover practically fully the smith chart. Furthermore, very wide band and low loss operation of the tuner has been demonstrated. Measured results have been demonstrated over 20 ... 110 GHz.

In printable electronics and optics, embedding of optoelectrical, optical, and electrical functionalities into low-cost products like packages and printed matter can be used to increase their information content. These functionalities make also possible the realization of new type of entertaining, impressive or guiding effects on the product packages and printed matter. For these purposes, components, such as, displays, photodetectors, light sources, solar cells, battery elements, diffractive optical elements, lightguides, electrical conductors, resistors, transistors and switching elements and their integration to functional modules are required. Recent developments have enabled to fabricate these functional components on flexible paper and plastic like substrates by gravure printing, embossing, digital printing, offset and screen printing.

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