Millimeter-Wave and Terahertz Devices Based on MEMS Concepts

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The higher the frequency, the more significant are the losses. Therefore it is important even for semiconductors with relatively large energy gap to remove as much semiconducting material as possible. This leads to components and their circuits to be produced on thin semiconducting membranes where most of the substrate is etched away. It is then a relatively small step to employ mechanical motion of suitably structured devices for such properties as fine-tune phase shifting or power switching. Relevant technology details are presented. A number of active and passive components are described with their special operational behaviour.

INTRODUCTION

The loss behaviour of semiconducting materials is approximately given for the frequency range of interest and the material properties by

$$\tan\delta = \omega\varepsilon/\kappa \qquad (1)$$

where δ is the loss angle, κ and ε respectively the conductivity and the dielectric constant of the semiconductor and ω the angular frequency.
For ω in the mm-wave or THz region, the losses for GaAs and in particular for Silicon are substantial. Correspondingly, the frequency characteristics of filters, matching circuits and other parts of modern telecommunication electronics cannot be sharp. Therefore, it is generally considered essential to involve micromachining or MEMS techniques for higher frequencies.
Similarly the metal thickness has to be reduced to a level as determined by the skin effect of the metal resistivity. Also the isolation between components needs to be optimised. Again, often it is useful to remove material there to as much as possible for the maintenance of good stability and thus also device life times.
Various micromachining technologies have been developed for the implementation of micro-electromechanical systems (MEMS). We therefore developed optimised technological approaches for such systems including sub-µ components, which go down to nanometric quantum electronic dimensions.

FABRICATION TECHNIQUES

First the top structure is fabricated, possibly by multiple photoresist steps to obtain multiple metal and insulator structures such as suspended transmission lines for electromagnetic waves. Then the substrate is removed by multiple etch steps, both by dry and wet etching processes. The last etch process is terminated by an epitaxially in-built etch stop layer like GaAlAs of only a few monolayers thickness.
Often metal thickness can be adjusted by cathodic electrolytic steps. To optimise all these processes require often a systematic approach, where however the experience of particular technology laboratories is a significant help to shorten this effort.

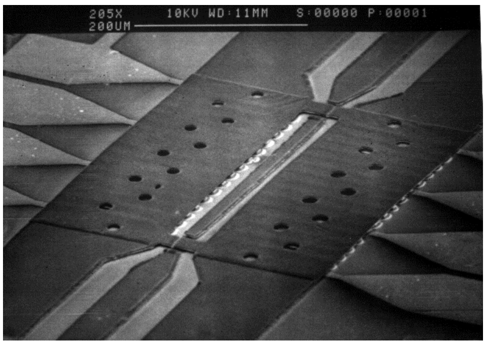

Figure 1: Micromachined microwave-power sensor on GaAs: ohmic losses in the central conductor of a coplanar waveguide are used. The ground electrode is lifted above (air bridge structure) the membrane in order to avoid thermal losses due to additional metal on the membrane.

As a particular example Figure 1 shows a MEMS structure for microwave bolometry, where the coplanar transmission lines have the ground metallisation areas suspended above the thin Seebeck bridges to hold the slightly wave-power absorbing semiconductor membrane (1,2). The experimental results of a similar sensing structure for frequencies up to 80 GHz is given by Figure 2.

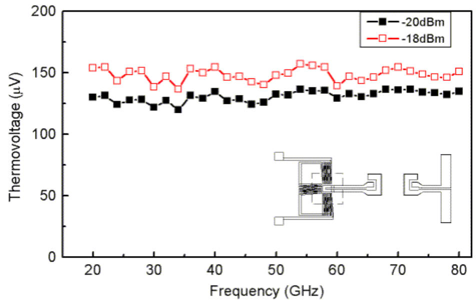

Figure 2: Response of a membrane-based mm-wave sensor for the frequency range up to 80GHz.

HIGH-Q MEMS INDUCTORS, -CAPACITORS AND -FILTERS AND OTHER PASSIVE COMPONENTS

The opportunities for such components with as little material as possible for a minimisation of losses are very widespread, where even removal of semiconductor material next to conductor lines can be practised, as long as the resulting structures remain stable for long-life operation. Figure 3 shows typical filters for frequencies near 0.6 THz. In a similar manner circuits need to be designed which achieve wave matching or noise matching or any other signal handling capability.

An important requirement is to match lines going on a chip part with substrate (for stability purposes) to another part, where the substrate is removed. The effort here involves, depending on the used etching system, the profile of the transition from the substrate to the membrane.

SCHOTTKY DIODES FOR MIXING

The traditional technique of Schottky-diode structures for highest frequencies has been a small Schottky metal contact surrounded by an insulating layer of a larger thickness than the metal so that a whisker wire can be located over the metal surface. For optimum noise performance (lowest noise temperature of a mixer) the thermal expansion coefficient of the insulating layer must match that of the semiconductor, and the metal must be deposited by pulsed electrolytic deposition of a complex know-how procedure as developed over many years of technology optimisation. Indeed the metal must be deposited without damage to the underlying semiconductor and the metal must have an optimised grain structure at the interface. The higher the frequency of operation the smaller the metal pad needs to be, for THz typically below 1 µm according to particular design equations. The noise temperature obtained with our Schottky diodes for 2.5 THz by the university of Erlangen is 16 000 K which is certainly among the best values achieved so far (3). The substrate material under the matrix of Schottky structures should again be removed. For particular power applications the active layer can also be transferred to a gold header in order to obtain good heat sinking.

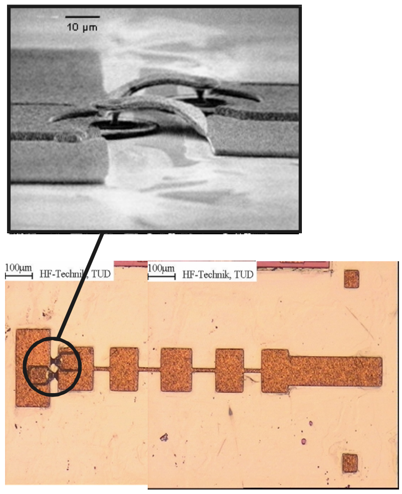

Figure 3: SEM picture of anti-parallel Schottky diodes integrated with microstrip filter

For many applications, it is of interest to fabricate planar structures where the whisker is replaced by short Gold tower, fabricated by special resist technology and connected at its top directly to a free standing transmission line. These structures can then be connected monolithically with filters and other passive components, all in the MEMS technology domain. Even more complex planar realisations concern anti-parallel diode structures, which require a large number of lithography and other technology steps.

SCHOTTKY AND HETEROBARRIER VARACTORS AND CHARGE-SWING CONCEPTS FOR HARMONIC EXTRACTION

Space charge layer modulation can be obtained by the use of single or multiple energy barrier peaks. The traditional methods are p.n. junctions, which however are only suitable for relatively small frequencies since minority carrier removal is a relatively slow process. Better is here therefore the Schottky diode, which is commonly being used for frequencies well into the upper THz region. Here the nonlinearity of the diode capacitance is generally used. An important effort is needed by the semiconductor epitaxialist , in order to obtain large reverse bias breakdown voltages. Good results are for example 16 Volt for GaAs (4).

Instead of Schottky-barrier energy pinning by the metal-semiconductor transition (which is not available for all types of semiconductor materials), heterojunction energy barriers can be produced by epitaxial growth of such sandwiches as GaAs-GaAlAs-GaAs with n-doped layers in the GaAs. Here then symmetrical capacitance-voltage nonlinearities can be obtained (5). HBV's of various epitaxial structures have been produced by us and successfully used for harmonic extraction by other laboratories (6). Figure 4 shows an image of the fabricated HBV chip, which is 100 µm square and 30 µm thick, with gold substrate on the back and mesas with a honeycomb anode array on the front. The thick gold substrate promotes the mechanical stability of the device and simplifies the handling as well as serves as heat-sink.

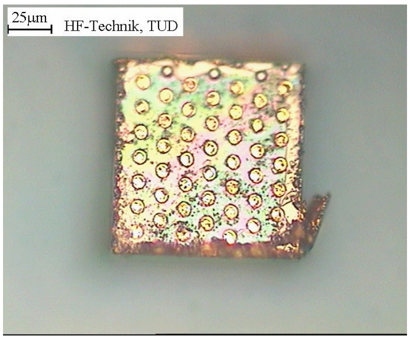

Figure 4: Fabricated two-barrier HBV on gold substrate

Instead of space-charge layer width modulation, other concepts such as space charge bunch transfer is under investigation by us. Here the Charge Swing uses heterobarrier epitaxial structures such that a charge bunch is transferred either via a drift space or via a quantum cascade tunnelling distance (particularly promising for high speed transition in view of increased frequencies of operation) between two trapping valleys. Similar to the old step recovery diode, here the current abruptly terminates during half the positive or negative voltage swing of mm-waves. In this way, a large content of harmonic waves is created with good efficiency. In this manner, the device is equivalent to two step-recovery diodes in opposition (7).

OTHER NEW CONCEPTS OF TERAHERTZ DEVICES

Many important developments for THz devices can be expected with the concepts of quantum cascade devices. THz signal generation has been reported on the basis of quantum cascade techniques wholly in the conduction band. Even the emission of coherent THz waves by stimulated emission has been reported. This approach comes from stimulated light emission and has made considerable progress via the infrared region into the upper THz region. It can be expected that many further developments occur, and also that new device concepts for the THz region will be made.

So far, only semiconductor concepts are reviewed here. For completeness however it should be mentioned that numerous other possibilities exist such as the Superconductor-Insulator-Superconductor diodes (abbreviated as SIS diodes), which however can only be operated at extremely frequencies, whereas all the semiconductor devices reviewed here are usually suitable for room-temperature operation.

CONCLUSIONS

The field of mm- and THz-wave electronics is growing in order to satisfy all the applications in this area. It is strongly based on nanometric structuring with significant quantum electronic effects. Epitaxy and lateral nm-lithography are becoming more and more important. For a satisfactory operation, MEMS techniques have to be widely used.

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