Electron permeable membranes for MEMS electron sources

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Received 23 September 2005; received in revised form 13 April 2006; accepted 21 April 2006
Available online 27 June 2006

Abstract

Systems that employ electron beams like electron microscopes or devices for electron beam welding all require high vacuum technology to handle the electrons. This paper describes design, simulation and realization of electron permeable membranes for use in future atmospheric micro electron sources.

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Keywords: Electron permeable membrane; Thin-film technology; Micro electron source transmittance; Support structure

1. Introduction

Many devices for material analysis and material treatment employ beams of free electrons. However, all these applications premise high vacuum conditions, which leads to voluminous devices with complex pumping systems, laborious sample preparation and restrictions in the sample size.

For a future application in the field of hand-held material testing based on electron beam analysis we are developing miniaturized electron beam sources \[1\]. Our approach to reach this goal makes use MEMS elements for electron generation and acceleration and includes electron-transmissive thin-film membranes that shield the vacuum inside the electron source from the ambient pressure and allow the electrons to travel into air. The schematic configuration of such a micro electron source is shown in Fig. 1. It mainly consists of four different components: the emitter array, insulating spacers, an acceleration grid and the electron permeable membrane. The latter is focus of this paper.

It has recently been shown, that electrons with relatively small energies of 3–5 keV generated in vacuum can be transferred through very thin membranes of porous alumina \[3,4\] to ambient conditions and are able to traverse a few hundred microns in air before they hit the target material \[2\]. However, with regard to reliability and robustness under practical operation conditions the high fragility of thin alumina films reduces their applicability in technical products. For this reason we have chosen a MEMS approach to realize electron-transmissive membranes for use in later product applications. However, the development did not aim to realize membranes of minimum layer thickness as feasible with MEMS technology. Here, we describe design, fabrication and first characterization of these membranes.

2. Material selection and transmission simulations

Basic requirement on the material used for the fabrication of electron-transmissive membranes is a low atomic number in order to keep the energy loss and angular dispersion of the traversing electrons small. Furthermore, the material has to have sufficient mechanical strength when applied as a thin-film and should be compatible to the other micro components of the electron source. Simulation calculations using the Monte-Carlo Simulator MOCASIM have been carried out for different thin-film materials to estimate their permeability for low energy electrons. As an example, the diagram in Fig. 2 shows the simulated transmission behavior for a membrane of 100 nm thickness in dependence of the electron energy for the materials alumina, diamond, beryllium, silicon oxide, silicon nitride, and silicon carbide. From the physical point of view, beryllium would the best choice. However, it is poisonous, requires special safety precautions for processing and therefore ineligible for use. On

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doi:10.1016/j.sna.2006.04.042
the basis of published work from other research groups [1,2,5] and due to the availability of an optimised low pressure chemical vapor deposition (LPCVD)-process silicon nitride was selected as membrane material. For practical evaluation transmission experiments with silicon nitride membranes of 100 nm thickness have been carried out employing the beam and the detection system (Fraraday cup) of an electron microscope. The results are shown in Fig. 3. It can be seen that for electron energies between 10 and 30 keV the transmission ranges from about 8–95%. The measurements are in good accordance to published results from other groups [5].

3. Design and fabrication technology

As the membranes have to be able to withstand atmospheric pressure an appropriate support structure is required to prevent breakage. This can be realized by a hexagonal silicon grid structure, which takes up the forces acting on the membrane when exposed to pressure. In order to estimate the required mechanical properties of the support structure FEM calculations with the simulation tool Femlab have been carried out for different grid geometries and membrane thickness of 50, 100, 200 and 300 nm. It was found, that for a given membrane area of 1.5 mm × 1.5 mm a grid diameter of 10 μm, a web width of 3 μm and a height of 20 μm covered with a 100 nm silicon nitride membrane should be able to withstand a pressure difference of 1 bar. An example of the simulation calculations is given in Fig. 4 demonstrating the tensile stress distribution of a single membrane-covered hexagon. Fig. 5 gives the dependency of the tensile stress from the pressure. It can be seen, that for the geometrical parameters given above the resulting stress (black curve) stays reasonably below the rupture stress of silicon nitride (red line).

It is clear, that the presence of the support structure reduces the open membrane area which leads to a corresponding decrease in the electron transmission rate. For the selected geometry, this is about 40%. Furthermore, as the supporting grid structure has a height 20 μm and a mesh width of about 10 μm only those membranes could be used. It can be seen, that for the geometrical parameters given above the resulting stress (black curve) stays reasonably below the rupture stress of silicon nitride (red line).
electrons can pass through the membrane that have an incident angle close to 90°. This applies particularly for electrons that impinge close to the borders of the membrane. Fig. 6 shows the computed electron transmission through a single grid mesh as a function of the entry point on the membrane with the electron energy as an additional parameter. The influence of the grid walls on the transmission rate can clearly be seen.

In the following the main steps of the processing of the supported membranes is described. The manufacturing is performed on a silicon on insulator (SOI) wafers with a device layer thickness of 20 mm. As the first step the hexagon grid structure with the dimensions given above is transferred in photo resist (Fig. 7). Subsequently, the advanced silicon etching (ASE™) process is applied to the device layer to realize the grid structure (Fig. 8). After removal of the resist, thermal oxide with a thickness of approximately 500 nm is grown by wet oxidation at 1100 °C (Fig. 9). The resulting oxide layer provides an additional protection of the grid structure during the KOH-etching, which is later required to open the backside of the wafer. Now, the silicon nitride membrane is deposited by a LPCVD process at approx. 770 °C (Fig. 9). With this step the processing of the device layer is finished and the backside processing starts. At first, a resist pattern for the opening of the silicon nitride and the silicon oxide layer is realized by photo lithography. Using a two-step RIE process the nitride and oxide layer is opened (Fig. 10). The resulting nitride/oxide pattern serves as a mask for the subsequent KOH wet etch of the silicon window (Fig. 11).
Fig. 10. Backside: predefines the large window opening silicon nitride.

Fig. 11. Electron-transmissive MEMS window after KOH etch.

The process runs with a KOH concentration of 20% at 80 °C. Finally, the buried oxide layer is removed from the structured backside of the device layer. This is realized by a wet etch process in buffered hydrofluoric acid.

4. Characterization

First characterization of the membranes has been performed by SEM inspection (Fig. 12). The image on the left side shows a close-up of a part of the membrane including the support structure, on the right a photo of the whole membrane chip is shown. Fig. 13 shows the cross-section of the membrane structure. The substructure at the front side of the grid walls is due to the periodic switching of the ASE™ process.

First experimental tests have been performed using the setup the electron microscope setup mentioned above. The transmittance was determined for electron energies down to 2 keV, which was the detection limit of the setup. The results are shown in Fig. 14. Compared to Fig. 3 the measured transmittance is reduced by about 30%. This is due to the supporting grid which

Fig. 12. Left: hexagonal supporting silicon grid. Right: electron window chip. The transmissive area is 2.4 mm × 2.4 mm.

Fig. 13. Cross-section of a 100 nm silicon nitride electron permeable membrane including the silicon support structure for the realization of the specified pressure resistance of 1 bar.
reduces the open membrane area and hence, leads to an additional loss of electrons.

As the beam current of the electron microscope is limited in the low energy range to some picoamperes, an arrangement which employs a thermionic emitter yielding a higher current has been setup. Acceleration of the electrons was obtained by applying high voltage from an external source between the grounded emitter and the silicon support grid of the membrane. The latter exhibits a rather good electrical conductivity as it is made from a doped silicon. Using this setup the dependency of the transmittance from the energy of the incident electrons has been experimentally investigated in more detail in the low energy range 0–4.5 keV. The result is shown in Fig. 15. It can be seen that electron transmission starts at an energy of about 1.5 keV. At 2.5 keV the transmission is already in the order of 14% and meets above 3 keV the results of preceding measurement (Fig. 14).

Upon completion of the membranes a first assembly of the micro electron source has been realized. The device as shown in Fig. 16 follows basically the layout given in Fig. 1 and contains all components including a thermionic emitter.

5. Conclusions

Electron-transmissive silicon nitride membranes for use in miniaturized electron sources have been realized and experimentally tested. Design and layout of the membranes has been based on Monte-Carlo simulations for the electron transmittance as well as on FEM calculations for the determination of the mechanical parameters. The realized membranes cover an area of 1.5 mm × 1.5 mm and are equipped with a hexagon support structure in order to provide stability against atmospheric pressure.

The measured electron transmission corresponds in the high voltage range of 10–30 keV to the state of the art. First experimental data has been obtained for the energy range below 10 keV. Here transmission arises at 1.5 keV reaches 25–30% at 5 keV which is expected to be sufficient for the planned application in material analysis. Future work will be focused on the investigation of micro electron sources and their applicability under ambient conditions.

Acknowledgment

The work presented here has been funded by the German DFG (SFB622) as well by the state of Rhineland—Palatinate.

References

Biographies

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