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A field-emission pressure sensor of nano-crystalline silicon film*

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Abstract The prototype of a field-emission pressure sensor with a novel structure based on the quantum tunnel effect is designed and manufactured, where a cathode emitter array is fabricated on the same silicon plate as the sensible film. For an integrated structure, not only the alignment and vacuum bonding between the anode and cathode are easy to be realized, but also a fine sensibility is guaranteed. For example, the measured current density emitted from the effective area of the sensor can reach 53.5 A/m^2 when the exterior electric field is 5.6×10^5 V/m. Furthermore, it is demonstrated by finite element method simulation that the reduction in sensor sensitivity caused by emitters on the sensible film is negligible. The difference between the maximum deflections of the sensible films with and without emitters under specified pressure is less than 0.4%. Therefore, it can be concluded that the novel field-emission sensor structure is reasonable.

Keywords: **nano-crystalline silicon film, field-emission pressure sensor, finite element method (FEM) simulation.**

Integrated, multi-functional and intelligent sensors are a main development trend of modern sensor technology, which are closely related to the growth of the micro and nano sensor technology based on micro-electro-mechanical systems (MEMS) technique. With the development of microelectronics, MEMS technology and vacuum-electronics, the design of novel vacuum field-emission pressure sensors based on the quantum tunnel effect has been becoming a focus of developing mechanical sensors of high sensitivity and new mechanism[1~6]. Compared with other types of sensors, e.g. piezoresistance and capacitance sensors, the vacuum electronic pressure sensor has some superior properties, including high sensitivity, good endurance at high and low temperatures, radiation resistance and small volume. It could be used in various civil and military engineering fields to measure pressure, flow velocity, fluid height, acoustic wave intensity and so on. Especially, it can be used in the tactile system of intelligent robotics and in severe operating environments.

In this paper, the manufacture of a vacuum field-emission pressure sensor is presented, using the excellent field-emission property of low dimension nano-crystalline silicon film[7,8], as the emission part. The combination of the nano-technology, vacuum microelectronics and sensor technology can raise the emission efficiency of the sensor, and then improve the sensibility.

1 Principle and design of the vacuum field-emission pressure sensor

In a conventional vacuum field-emission pressure sensor, the sensible film is designed as the

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anodic component separated from the cathodic one. In this case, there are two big technique difficulties, namely the alignment and vacuum bonding between the anode and cathode. So a novel vacuum field-emission pressure sensor structure with the cathode emitter array and the sensible film fabricated on the same silicon plate was advanced[6], which not only simplified the technique but ensured the high sensibility of the sensor. The schematic diagram of the field-emission pressure sensor is shown in Figure 1.

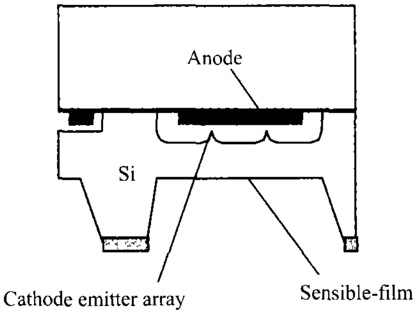

Fig. 1 Schematic diagram of the novel structure of a vacuum field-emission pressure sensor.

The sensor is mostly made up of the anode collector, cathode emitter array, sensible film receiving exterior pressure and the vacuum micro-chamber between the cathode and anode. The design principle of the sensor is based on the Fowler-Nordheim field emission theory. With a positive bias voltage between the cathode and anode, the potential hill of the cathode surface decreases or becomes thinner. This will induce a quantum tunnel effect, and field-enhanced electrons will obviously be emitted at the tips of cathode emitters, which leads to a positive direction current. Such a field emission current is sensible to the distance change between the cathode and anode. So the sensor device can be designed to monitor the exterior pressure which causes the distance change through measuring the emission current.

In this paper, the structure and geometric parameters of the sensor, the shape of emitters, and the surface work function of material are all optimized. Based on these efforts, a new nano-crystalline silicon film field-emission pressure sensor is designed.

2 Manufacture of the nano-crystalline silicon film field-emission pressure sensor

The manufacture of the nano-crystalline silicon film field-emission pressure sensor is essentially an MEMS technique. The key steps include some single and combined courses, such as the fabrication of silicon cone array, the formation of cathode emitter array covered with a nano-crystalline silicon film, the construction of the field-emission diode and etching of the sensible film.

More than 300 units were manufactured on a double-polished N type (100) Si plate. Their thickness, diameter and resistivity are 400 μm, 10 cm and 4 ~ 7 $\Omega \cdot$cm, respectively. The effective area of each unit (inside the sensor) is 3.5 mm × 4 mm. There is left a wide gap of 1 mm between the units for dividing part. The dimension of the quadrate mask is about 5 μm × 5 μm, and the equally distributed interval space is 5 μm. In order to obtain the sensor structure shown in Fig. 1, five plates were designed with five operations of lithography. The micro-sealed field-emission pressure sensor was completed using the techniques of the silicon cathode, glass anode and silicon-glass bonding.

The specific experimental results are shown as follows. The cathode of the unit sensor device is fabricated by isotropic etching first, and then the oxide tip sharpens with the mask according to the design requirements. The whole field emission area is 500 μm × 500 μm, and 2500 (50 × 50 array) emitters of almost the same geometric shape are well-distributed inside it. The height and curvature radius of each emitter are 1.7 μm and 40 ~ 50 nm, respectively. The interval distance of emitters is 10 μm. A scanning electron microscope (SEM) analysis of the cathode silicon cone array is shown in Fig. 2, which indicates that the uniformity of the sample can meet the emission function requirement of the field-emission pressure sensor.

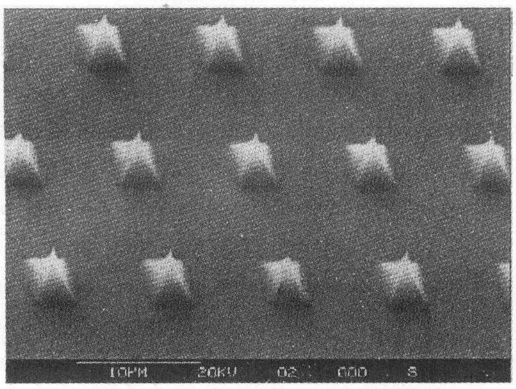

Fig. 2 SEM of the sensor cathode silicon cone array.

The nano-crystalline silicon film was deposited on the silicon array by chemical vapor deposition (CVD) method, with the grain dimension and thickness of the film being 3 ~ 9 nm and 30 ~ 40 nm, respectively. SEM analysis indicates that the morphologic structure of the silicon array is not influenced by the deposition of the nano-crystalline silicon film except for the increased curvature radius of the silicon cone. It can be assumed that the deposited nano-crystalline silicon film can perform the important function mostly as the field-emission material, and the silicon cone just plays the role of a carrier. Evidentially, the emission characteristics of the nano-film material should be verified.

The Ti/Pt/Au-plating glass served as the anode, and the sensor diode structure was constructed by the static bonding between the cathode and anode. The distance from the anode to the tips of the cathode cone emitter was kept at 1.8 μm when no load was acting on the sensible film. The sensible film was formed by etching. The prototype of the nano-crystalline silicon film field-emission pressure sensor was thus completed (Figure 1).

A 50 × 50 field-emitters array was fabricated inside the 500 μm × 500 μm central area of the sensor, with a density of 10^6 emitters/cm^2. Assuming that the mean grain dimension of the nano-silicon film is 5 nm, then the surface density can reach 4×10^{12} grains/cm^2. And so, the number of the grains covering each emitter surface is 4×10^6. The scanning tunneling microscope (STM) observation showed that the crystal grains rose and fell on the nano-silicon film surface. Only when the electric field was applied, each crystal grain would be activated as an emission central point, and obviously, enhance the emission current and consequently increase the sensor sensitivity. For example, when the applied exterior electric field was $5.6 \times 10^5\ V \cdot m^{-1}$, the current density of the effective area of the sensor could reach $53.5\ A \cdot m^{-2}$, as measured by an transistor tester HP4145B. Supposing that each emitter can emit an even current, the emission current density of each emitter can reach $0.02\ A \cdot m^{-2}$, which clearly shows an excellent emission ability of the sensor.

3 FEM-simulation of the sensible film deformation

The prototype of the sensor manufactured with the integrated cathode emitter array and sensible film has been easily realized through the MEMS technique. But on the other hand, the deformation state of the sensible film becomes more complicated, as compared with the conventional sensor where the emitter and the sensible film are separated. For the latter, the deformation of the sensible film caused by the exterior pressure can be approximately calculated using the plate-shell theory under given boundary conditions. If the boundary shape of the sensible film is regular, e.g. rectangular, and its deflection is so small that the stress-strain relation in the film can be regarded as linear, the calculated deflection is accurate enough. But for the sensible film with emitters, its deformation can not be calculated with a sufficient precision by the plate-shell theory due to the complicated geometric boundary conditions. Therefore, the deformation state of the sensible film with emitters is predicted using the FEM-simulation.

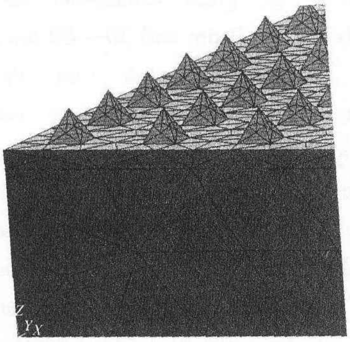

Fig. 3 FEM-mesh of the emitters-film structure.

A 3-D solid model of the emitters-film structure is first constructed exactly, where the dimension of the sensible film is 670 μm × 670 μm × 20 μm. It is then meshed into tetrahedron elements. Because of the different shapes of emitters and sensible film, before meshing, the structure is divided into three parts. Each of them has a different element size. This can lead to a compromise between the calculation precision and CPU time. Considering its symmetry, only one-fourth of the emitters-film structure is used in the FEM-simulation. The elasticity module and Poisson's coefficient of both film and emitters in the [100] crystal orientation are $E = 1.67 \times 10^5$ MPa and $\upsilon = 0.35$, respectively. Fig. 3 gives a part of the meshed emitters-film structure, in which the left vertical edge line is the central normal symmetric axis of the sensible film, where the maximum deflection will appear.

The deformation configuration of the emitters-film structure is presented in Figure 4.

Figure 4 shows that the distortion of the sensible film, caused by emitters, is very small. The simulation result shows that, with the same exterior pressure acting on the sensible film, the difference between the maximum deflections of the sensible films with and without emitters is also quite small (Table 1).

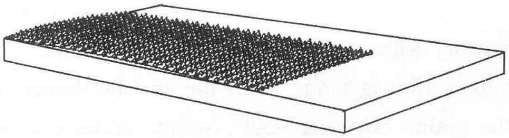

Fig. 4 Deformation configuration of the one-fourth emitters-film structure.

Table 1 Maximum deflections of the two types of sensible films

Applied pressure/Mpa	Maximum deflection of film/μm	
	with emitters	without emitters
0.25	0.458	0.459
1.0	1.830	1.836

From Table 1, it can be estimated that the relative difference in the maximum deflections in the above two cases is less than 0.33%. This means that the influence of the emitters on the deformation of the sensible film under a static pressure is limited.

The designed film field-emission pressure sensor of nano-crystalline silicon is not only simple in its structure, but also has high sensitivity as is demonstrated by experiments. Based on the 3-D solid model of the sensible film with emitters and the FEM-simulation, the deformation state of the sensor is predicted. From the experimental and simulation results, it can be concluded that the emitters-film-integrated sensor structure proposed here is simple in its sensor structure and possesses high sensibility.

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