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Silicon Needle Transducer

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It has been known for some time that large mechanical stresses ($\sim 10^8 - 10^{11}$ dynes/cm) have significant effects on the electrical characteristics of p-n junctions [1 - 3]. These changes in characteristics, for uniaxial stresses, result from stress-induced changes in the energy band structure of the semiconductor material[4]. The net effect of stress is to decrease the average energy gap of the material. This affects the junction parameters in two ways: first, it causes an increase in the minority carrier concentration and, second, it can increase or decrease the carrier recombination rate.

In diodes, stress causes the saturation current to increase. At high stress levels, the forward diode current is

$$I = I_s \left[\exp qV/kT - 1\right]$$

where

$$I_s \approx I_{so} \exp c\sigma ,$$

c is a constant depending on material and orientation and σ is the magnitude of the stress.

The practical utilization of this piezojunction phenomenon is limited primarily by two factors. First, the stress levels required to produce the effect are extremely large--on the order of 10^4 atmospheres. In order that the associated force levels remain reasonable, it is necessary to apply the force over a very small area ($\sim$mils^2). Also this stress must be very accurately coupled to the junction area of the semiconductor device of interest. Care must be taken to avoid overstressing of the device since the stresses required to produce the phenomenon are near the fracture strength of the semiconductor material.

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The major difficulty in fabricating practical transducers based on the piezojunction phenomenon has been the application of the required stress to the proper position on the semiconductor. Along with the limitations described, it is also desirable to stress the entire junction to avoid unstressed regions of the junction from controlling the electrical properties.

Heretofore, the most successful method of stress application has been by means of a spherical indentor point such as a steel, diamond, or sapphire phonograph needle. This helps to avoid overstressing since the stressed area increases with applied force. Also, the fracture strength appears to be higher when only a small area of a large sample is stressed. The major disadvantage of the indentor point method is the critical alignment between the point and the small junction. This alignment must be accomplished with the aid of a microscope. Any lateral movement of the indentor point after contact is made can drastically change the device characteristics or damage it permanently.

The search for a more reliable and less tedious method of stress application led to the semiconductor needle approach to the problem. The semiconductor needle transducer is simply an inversion of the indentor point method in that the indentor point is now made of silicon and the p-n junction device is formed on its apex. Stress is applied to the junction by forcing the apex of the needle onto a hard, conductive surface. Figure 1 is a sketch of the needle structure with a diode on the apex.

The needles are formed by electroetching one end of a rectangular silicon bar. The radius of curvature of the apex can be controlled to as low as one micron. Figure 2 is a photomicrograph of a typical needle along with a straight pin for comparison. The p-n junction or junctions are formed on the needle by using conventional photolithographic and diffusion techniques. Both mesa and planar types have been made. However, the planar types have oxide passivated junctions and are inherently more stable.

A photograph of the forward I-V characteristics for three stress levels in a planar silicon needle is shown in Figure 3. The curve to the far right represents zero stress with stress increasing for each curve in the direction of the origin. The horizontal scale is 0.2 V/cm and the vertical scale is 0.01 mA/cm. In addition to increasing the forward and reverse currents, the breakdown characteristics are softened. Both the junction depth and the radius of curvature of the needle tip are critical parameters in determining the sensitivity of diode needles.

Basically the silicon needle is a transducer of force and displacement. For the purpose of demonstrating its practical usefulness, the silicon needle transducer has been incorporated into a laboratory accelerometer. A photograph of the accelerometer is shown in Figure 4. The needle is attached to the housing and the seismic mass is pressed against the needle tip by a spring. The spring provides a dc stress bias on the junction. Acceleration acting on the mass varies the stress level about the dc point and changes the electrical characteristics of the junction. The accelerometer was calibrated by rotating it through 360° in the vertical plane. The calibration curve is shown in Figure 5.

In summary, the silicon needle transducer is a unique method of utilizing the piezojunction effect. Its major advantages over other known methods are that it eliminates critical alignment problems and can be made more sensitive to stress.

Footnotes and References

This work was supported by the Office of Advanced Research and Technology, National Aeronautics and Space Administration, under Contract No. NASr-222.

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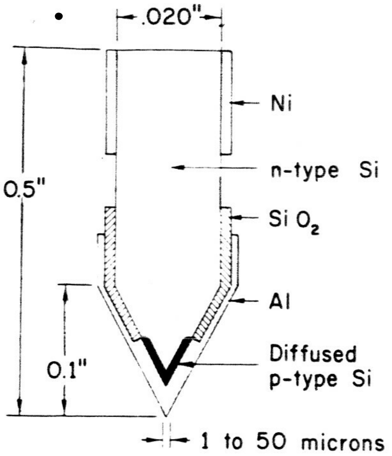

Figure 1. Silicon needle transducer, planar type.

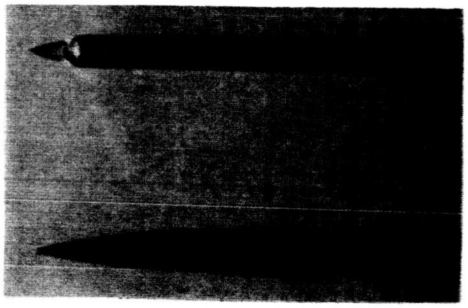

Figure 2. Photomicrograph of a silicon needle transducer compared to a straight pin.

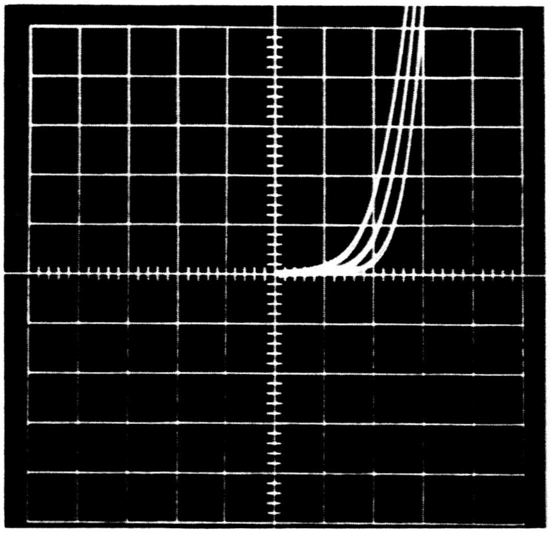

Figure 3. Forward I-V characteristics of a planar silicon needle transducer.

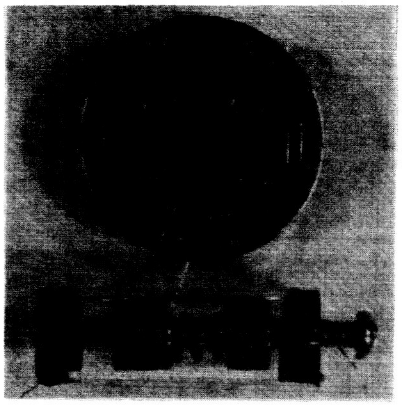

Figure 4. Photograph of an accelerometer using the silicon needle transducer.

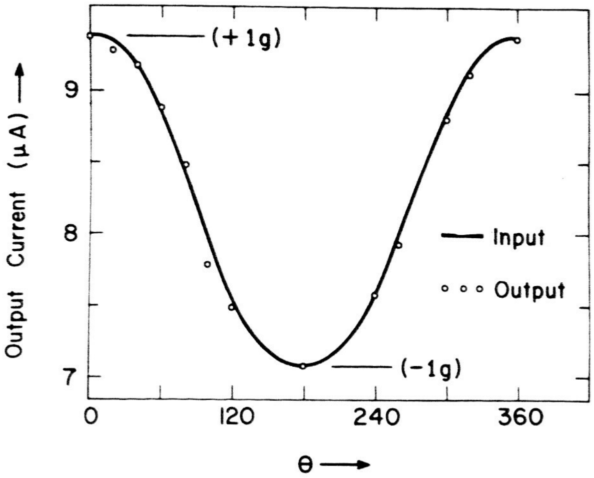

Fig. 5. Accelerometer calibration curve.