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A Manganin Foil Sensor for Small Uniaxial Stress

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We describe a simple manganin foil resistance manometer for uniaxial stress measurements. The manometer functions at low pressures and over a range of temperatures. In this design no temperature seasoning is necessary, although the manometer must be prestressed to the upper end of the desired pressure range. The prestress pressure cannot be increased arbitrarily; irreversibility arising from shear stress limits its range. Attempting larger pressures yields irreproducible resistance measurements.

Manganin has been used and studied extensively as a pressure manometer for decades, both for hydrostatic pressure and for shock waves. Its resistivity is linear up to high pressures, described by a piezoresistance coefficient $\Delta R/R$. Near room temperature the resistivity has little temperature-dependence, due to a nearby maximum in the resistivity. Hence any temperature changes induced through compression do not interfere with the reading of a resistance manometer. Also, while the resistivity is temperature-dependent, at fixed temperature it maintains its linearity in pressure.

Typical commercial manganin gauges use wire coils or grids manufactured from very thin foil. Here we discuss a simple home-made manganin foil gauge for uniaxial stress measurements. Our work involves lower pressures than usual for manganin manometers, and we find that for our purposes various steps in setting up the manometer become unnecessary. A main advantage is the ease of making the gauge and adapting it to the geometry of the experiment.

One such manometer, shown in Figure 1, is a 10 mm by 3 mm piece of manganin foil, 0.5 mm thick. The foil is inserted into a pressure column, with stress applied through a circular spacer to a 3 mm diameter region. Platinum wires for resistance measurements are spot-welded to the large top surface of the manganin foil, outside of the stressed region, making these connections very simple. Using a foil larger than the pressure column also helps in assembling the column; with a small piece it is more difficult to ascertain that the spacers and manometer are properly positioned and aligned. The manganin response is then used to determine the pressure on a sample located elsewhere in the pressure column.

We use two different pressure setups for calibrating the manganin manometer and confirming that its behavior is reproducible. In one the stress is applied by tightening a screw; in the second it comes from pressurizing a helium bellows. The latter setup is mounted on a dilution refrigerator, but in the work here we use it from room temperature down to liquid nitrogen temperature. Each apparatus has a piezoelectric in the pressure column to measure the applied stress. After calibration is complete we can transfer the manganin manometer to a different screw-operated pressure cell, which has too small a diameter to accommodate the piezoelectric sensors.

In previous experiments manganin pressure gauges often require "seasoning" to give reproducible results. The treatment typically includes both annealing to temperatures above and below room temperature and also applying a higher pressure than will be reached in the planned measurements. The high pressure may be applied multiple times, and may be interspersed with the thermal cycling.

In our uniaxial measurements, we find no effect from thermal cycling. However, prestressing is crucial to obtaining acceptable repeatability. We perform a single prestress at room temperature, applying a pressure $P_{ps}$ of typically about 2.2 kbar and waiting for a time from 2 to 40 minutes. Lengthening the wait time has no effect on subsequent measurements. For sufficiently small $P_{ps}$, the manometer’s subsequent response is repeatable for pressures below or even very slightly above $P_{ps}$. These pressures are extremely low compared to previous work, but we find that seasoning at a higher pressure does not expand the usable range of the manometer and can even degrade its subsequent performance.

After assembling the manometer and prestressing to a pressure $P_{ps}$, we measure the resistance of the manganin foil as we apply pressures below $P_{ps}$. We use several different pressures and apply each one repeatedly, returning to zero pressure in

![Diagram](image-url)
between. This confirms the reproducibility of the measurements and the linearity of $\Delta R$ with applied pressure. One such trace appears in Figure 2.

To compare with previous work, we consider the pressure coefficient of resistance $\Delta R/R_p$, where $\Delta R = R - R_0$. For the manometer with data shown here, the value is $7.8 \times 10^{-4}$ kbar$^{-1}$. The effect of pressure on $\Delta R/R_p$ should be independent of the manometer geometry, as long as the pressure is applied to the entire manometer. Since we apply pressure only to a portion of the current path for the resistance measurement, we expect the pressure to have a reduced effect on $\Delta R/R_p$.

The separation between our inner contacts is a factor of two to three larger than the diameter of the region under pressure. Since pressure affects the resistivity along only a portion of the measured region, our $\Delta R/R_p$ should be reduced by a factor of two to three, compared to the value when pressure is applied to an entire manometer. This is consistent with previous measurements for both uniaxial[6,7] and hydrostatic[1,2] pressure, which find pressure coefficients of resistance from $2 \times 10^{-3}$ to $2.5 \times 10^{-3}$ kbar$^{-1}$.

For applied pressures below the prestress pressure, we have performed several dozen pressure cycles with no indication of a change in the pressure coefficient of resistance or in the baseline resistance. This changes dramatically if the applied pressure exceeds $P_{ps}$, or if the prestress pressure exceeds a maximum effective prestress pressure $P_{max}$. For $P_{ps} > P_{max}$, the behavior at pressures above $P_{max}$ but below $P_{ps}$ is not reproducible and can lead to shifts in the floor resistance. For this geometry, we find $P_{max} \approx 2$ kbar. Figure 3 exhibits this behavior, with the resistance rising sharply each time a pressure above 2 kbar is applied. Removing the pressure shows that the ambient-pressure resistance itself increases on each pressure cycle. The pressure coefficient also decreases slightly after each application of excess pressure. Furthermore, increasing the prestress pressure does not eliminate the problem. Indeed, the five pressures above 2 kbar shown in Figure 3 occur in decreasing order, but each one nonetheless disrupts the manometer’s prior behavior.

Repeatable resistivity in manganin, linear with pressure, has been observed up to 180 kbar under hydrostatic conditions[8]. We attribute our irreversibility at much lower pressure to the fact that we apply stress only to a portion of the manganin foil. Manganin is very sensitive to shear stress, as indicated by variations in the pressure coefficient for nominally identical setups once the pressure medium solidifies[9]. The circular edge of the spacer defines a crossover between the pressurized section of the foil and the remaining ambient-pressure region. The cylindrical sheet lying directly below the circular edge is subjected to significant shear stress, probably introducing defects in the foil. This is consistent with the abrupt increase in resistance observed each time the applied stress exceeds 2 kbar in Figure 3, as additional defects are created. Upon repeated cycling we find no indication that resistance stabilizes, but the pressure coefficient decreases and the manometer becomes less useful. These observations are consistent with each pressure application creating new defects, primarily near the edge of the previous region of high defect density. As the defects begin to populate the portion of the manometer under the spacer, its pressure response changes.

To test the importance of the shear stress, we assembled smaller manganin manometers with the spacers pressing on...
the entire foil. In this geometry we found no maximum pressure limit for repeatability. Our apparatus could apply stress only up to about 4 kbar. Nonetheless, the small manometers easily surpassed the $P_{max}$ observed for the larger devices. These observations support previous evidence, mainly indirect, about the high sensitivity of manganin to shear stress \cite{1, 9}. Despite the pressure limitation, for low pressures the larger manometer foil setup has a significant advantage in ease of use. The smaller geometry requires attaching the measurement leads to the thin sides of the foil, which is much more challenging than placing them on the top surface. The small manometer also creates difficulties in the proper alignment of the pressure column. If the spacer piece slips to one side and acquires a slight angle, one edge of the spacer can bypass the manometer entirely.

Another benefit of a manganin manometer is the ability to monitor the stress directly at low temperature. In our screw-based pressure cells the stress is always applied at room temperature but may change through differential thermal contraction of the pressure cell materials. Empirically the resistance is linear in pressure at each temperature. One previous group reported further that the pressure coefficient is independent of temperature \cite{2}; others found that the pressure coefficient increases with temperature \cite{9, 10}. In our setup the pressure coefficient does have temperature-dependence. Nonetheless, our resistance data as a function of both temperature and pressure fit the form

$$R(p, T) = A + BT + CT^2 + Dp + E p T,$$

which allows us to determine pressure from measured temperature and resistance. The coefficients on the right depend on the exact geometry, so each new manometer must be calibrated in a trial run.

In addition to the manganin foil described above, we tested manganin manometers constructed from wire and from thinner foil. Neither was as successful. The wire manometer did not give reproducible results; this is in fact consistent with previous claims that seasoning pressures for wire manometers must exceed 4 kbar \cite{1, 8}. The thinner foil, 0.2 mm, was sanded down from the thicker material. The main advantage is a larger resistance, making measurements slightly easier. However, the pressure coefficient itself did not change, and the thicker foil is easier to work with and faster to set up.

We present a simple construction of a manganin resistance manometer, for use under low uniaxial stress. The design allows flexibility in the size and shape of the manometer, such as reducing the active area to make the gauge more sensitive when the pressure applied to a sample is very low. The external portions can also easily be shaped to fit the pressure cell. The setup requires only a single seasoning step of applying a pressure exceeding the desired measurement pressures. It also enables pressure sensing at low temperatures. The main limitation is that the stress on the gauge must remain below about 2 kbar. We show that this unusually low threshold stems from applied shear stress and confirm the sensitivity of manganin to shear.

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