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PRESSURE SENSITIVITY OF A GaAs FET OSCILLATOR

Richard A. Kiehl

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PRESSURE SENSITIVITY OF A GaAs FET OSCILLATOR

Richard A. Kiehl
Solid State Device Physics
Division 5133
Sandia National Laboratories
Albuquerque, New Mexico 87185

Abstract

Preliminary experimental results on the effect of hydrostatic pressure on the frequency of a GaAs FET microwave oscillator are presented. The oscillator is a common-source configuration in which the output-circuit reactance is determined by the inductance and capacitance of the pressure system test fixture.

Pressure sensitivities of -1.2 and -0.35 %/kbar are observed at 0 and 10 kbar, respectively. An examination is made of the various physical mechanisms which could account for the observed frequency shifts. It is shown that the frequency shift is primarily caused by variations in the output circuit capacitance resulting from pressure-induced changes in the permittivity of the FET's surroundings. Suggestions are made for utilizing the sensitivity of such an oscillator configuration for developing highly sensitive pressure transducers.

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I. INTRODUCTION

A need for the development of improved pressure sensors for a variety of high pressure environments has led to an interest in the pressure sensitivity of various microwave oscillators. For example, Chaffin¹ has recently proposed a new pressure transducer based on the pressure sensitivity of a Gunn diode oscillator caused by the pressure dependence of the intervalley electron transfer in GaAs.

Here we report preliminary results of an investigation of the pressure sensitivity of a field-effect microwave oscillator. To date, the use of a field effect transistor as a hydrostatic pressure transducer has been investigated² only insofar as the pressure dependence of the dc characteristics of a non-oscillating device is concerned. In the present investigation we deal specifically with pressure induced changes in the oscillation frequency of a GaAs FET.

II. EXPERIMENTAL PROCEDURE

The experiments were performed in a 30 kbar hydrostatic pressure system using a 50-50 mixture of normal pentane and isopentane as the pressure fluid. A description of the apparatus and general experimental procedures including pressure calibration has been given elsewhere.³

The FET used in the experiments was an HFET-1101 (Hewlett-Packard). The package of the device was opened by removing the metal cap, thereby allowing the fluid within the pressure

chamber to contact the FET chip itself. The manner in which the FET was connected to the test fixture in the pressure chamber is shown in Fig. 1. The only circuit element added to the FET was a 100 pF ceramic chip capacitor (ATC) which was connected between the gate and source leads. The external circuit produced by this arrangement can be viewed as a common-source configuration having reactive input and output load impedances determined by the chip capacitor and test fixture, respectively. Provided that the real part of the FET output impedance is negative, such a circuit will oscillate at the frequency for which the total reactance of the output circuit is zero.⁴

The RF output of the oscillator was monitored by capacitively coupling to the drain lead outside of the pressure apparatus. The spectrum of the RF output was viewed on an HP8555A/8552B spectrum analyzer while an HP5340A counter allowed accurate measurement of the frequency.

III. EXPERIMENTAL RESULTS

Prior to examining the pressure dependence of the oscillation frequency, the behavior of the oscillator under various bias conditions was examined at atmospheric pressure. In these experiments the pressure chamber was filled with fluid and then closed to prevent boiling of the pentane mixture, thereby assuring stable ambient conditions.

With the drain voltage V_d set equal to 5 V and the gate voltage V_g set at 0 V, the device exhibited stable oscillation at 5.197 GHz. When the gate voltage was increased beyond 0.5 V, the frequency was found to increase at a rate of approximately 55 MHz/V. This is shown in Fig. 2 where results have been plotted for V_g ranging from 0 V up to the pinch-off voltage of this device. For the results to follow V_g was set at 1 V. This corresponds to a point near the middle of the range between 0 V and pinch-off, as is desired in oscillator applications.

The dependence of the frequency on drain voltage V_d is shown in Fig. 3. It can be seen that the V_d dependence is quite small when V_d is greater than about 3 V. For V_d above this level, the sensitivity of the frequency to gate voltage is also relatively independent of V_d , as shown in Fig. 4. In the experiments to follow the drain voltage was set to 5 V, which corresponds to the nominal bias level specified for this device.

Having investigated the sensitivity of the oscillator to bias conditions at atmospheric pressure, the variation of the frequency with pressure was examined with V_g and V_d fixed at 1 and 5 V, respectively. (Digital voltmeters were employed to insure that these voltages did in fact remain fixed to 3 significant digits throughout the experiment.) The results are shown in Fig. 5, where frequency shift is plotted as a function of pressure. It is seen that the frequency decreases with

increasing pressure at a rate which is lower at higher pressures. In particular, the results show that the frequency varies at a rate of -63 MHz/kbar at low pressures and at a rate of -18 MHz/kbar as the pressure approaches 10 kbar. The values correspond to rates of -1.2 and -0.35 %/kbar, respectively.

The results shown in Fig. 5 represent data taken as the pressure was increased from the atmospheric level. In order to examine the repeatability of the measurement over a pressure cycle, data were also taken at 1 kbar intervals as the pressure was brought back down. At each point, the oscillation frequency was found to repeat itself within the tolerance of the systems manganin pressure gauge.

In order to investigate the interchangeability of different FET's, measurements were taken on a second HFET-1101 taken from the same manufacturer's lot. The data for this device and that of the previous device are shown in Fig. 6, where it can be seen that the pressure sensitivity in the two cases is much the same.

IV. PHYSICAL MECHANISM

A number of mechanisms could contribute to the oscillator's observed pressure sensitivity. We begin by considering those associated with changes in the FET's characteristics.

The drain-to-source conductance of the HFET-1101 at zero drain and gate bias is shown in Fig. 7 as a function of pressure. Figure 7 also shows the pressure dependence of the conductance of a GaAs Gunn diode at zero bias. It can be seen

that the conductance of both devices drops with increasing pressure. In the case of the Gunn diode, this drop is the result of a decrease in electron mobility. For pressures less than 10 kbar, the range shown in the figure, the decreased mobility is primarily due to a pressure-induced increase in the electron's effective mass.⁵ This mobility variation also contributes to the decrease in the FET's conductance with pressure. For the FET, however, there is an additional effect which is responsible for the more rapid drop in conductance seen for this device. This is the increase in Schottky barrier height with pressure that occurs at a rate of 11 mV/kbar, which corresponds to the rate of change of the separation between the control-valley and valence band edge.⁵ The increased barrier height causes an increase in the depletion region width and, therefore, affects the FET characteristic in the same way as would an increase in gate voltage.

Both the mobility and barrier height variations would be expected to affect the behavior of the FET oscillator in some way. The effect of the barrier height variation on the frequency can be determined from the data already presented in Fig. 2. Since the frequency varies with gate voltage at a rate of +55 MHz/V, the variation in barrier height would produce a frequency shift of +0.66 MHz/kbar or +0.013 %/kbar. Hence, in addition to being of the wrong sign, the effect of the barrier is too small to be a factor in the observed frequency shift.

Unlike the effect of changes in barrier height, the effect of changes in mobility can not be determined by varying the dc bias conditions. Since the mobility affects resistive rather than reactive elements, at first one might expect that it would only affect the amplitude and not the frequency of the oscillations. However, since the reactive part of the equivalent impedance of a circuit can depend upon the values of purely resistive elements, a mobility-dependent frequency is possible depending on the circuit topology.

As a result of the above, a detailed model of both the FET and its external circuit would be required in order to actually predict the mobility dependence of the frequency. However, based on the pressure dependence of the electron mobility in GaAs, it appears unlikely that the mobility variation is responsible for the observed frequency shift. Assuming a linear relation between frequency and mobility, the rate of change in frequency expected from the Gunn diode conductance data of Fig. 7 at low pressures ($-0.7\ \%/kbar$) is not too far from the measured value ($-1.2\ \%/kbar$). However, Fig. 7 shows that the rate of conductivity variation increases with pressure, whereas we have seen (Fig. 5) that the rate of frequency variation decreases with increasing pressure. As a result, at 10 kbars the conductivity variation has increased to $-1.5\ \%/kbar$ whereas the frequency variation has dropped to only $-0.35\ \%/kbar$.

Frequency shifts produced by changes in the capacitive elements of the FET due either to changes in the device dimensions or to changes in permittivity of GaAs under pressure

would also be too small to account for the observed shifts. The bulk modulus of GaAs is 744. kbar, so that the normalized pressure derivative of linear dimensions $(1/l)(\partial l/\partial p)$ is equal to -0.045 %/kbar. Being inversely proportional to the square root of capacitance, the frequency should vary as $l^{1/2}$ and hence at a rate of only -0.022 %/kbar. With regard to permittivity variations the normalized pressure derivative of the dielectric constant $(1/\epsilon)(\partial \epsilon/\partial p)$ is -0.17 %/kbar according to Samara.⁶ The frequency should vary as $\epsilon^{-1/2}$ and hence at a rate of +0.085 %/kbar. This is in the wrong direction in addition to being too small.

In the foregoing it has been shown that the observed pressure sensitivity of the oscillator does not result from changes within the FET itself. We now examine the sensitivity expected from other elements. The pressure sensitivity of the ceramic chip capacitor, which comprises the input circuit of the common-source configuration, was measured for pressures over the range of 0-10 kbar. The capacitance variation $(1/c)(\partial c/\partial p)$ was found to be -0.20 %/kbar throughout the entire range. Thus the frequency variation that would be expected from the input circuit is +0.10 %/kbar and would not explain the observed variation either.

In the output circuit, the capacitance arises from coupling between points on the source and drain lead wires and test fixture connections. Hence, the dielectric material of the output circuit "capacitors" is, for the most part, the pentane

pressure fluid itself. The pressure dependence of the relative dielectric constant of isopentane is available in the literature⁷ for pressures up to 2 kbar. Since this dependence is almost entirely a result of the fluid's volume change, this data can be extended to higher pressures using the pentane's known⁸ volume-pressure relationship. The results of doing so are shown in Fig. 8. Examination of the figure shows that the dielectric constant initially increases at a rapid rate (+7.8 %/kbar) and that this rate then drops to a lower and relatively constant level for pressures over 2 or 3 kbar (+0.83 %/kbar at 5 kbar).

This behavior is similar to that seen in the pressure dependence of the frequency. It may be noted that the frequency shifts expected from this data would be -3.9 and -0.42 %/kbar at 0 and 10 kbar, respectively, rather than the observed rates of -1.2 and -0.35 %/kbar. Such a difference would be expected, however, due to the fact that elements having negligible pressure dependence (e.g., the FET's source-to-drain capacitance) or a dependence that is different from that of pentane (e.g., capacitance supported by insulating material in the test fixture) also contribute to the output circuit capacitance.

To further examine the pressure dependence of the output circuit capacitance, the packaged FET was removed from the circuit and an HP4274A LCR meter was used to measure the capacitance across the source-drain pins of the fixture as the pressure was varied. The capacitance reading was "zeroed" at atmospheric

pressure so that only pressure induced changes in the capacitance would be measured. The results are shown in Fig. 9. An increase in capacitance with pressure at a rate which tails off in a manner similar to that seen in Fig. 8 is apparent. Since only the change in capacitance can be determined in this measurement (the total value of the capacitance is unknown), the normalized derivative ($1/C$) ($\partial C / \partial p$) cannot be determined for comparison with the frequency shift data. However, it is useful to examine the ratio of the slope $\partial C / \partial p$ for low and high pressures. From Fig. 9 one obtains a value of .035 and .011 pF/kbar at 0 and 10 kbar, respectively. Thus, if it is this capacitance variation that is responsible for the frequency shift, the frequency should vary 3.2 times faster with pressure at 0 kbar than it does at 10 kbar. Figure 5 shows that the frequency varies 3.4 times faster at 0 kbar than at 10 kbar, in very good agreement with this value.

V. CONCLUSION

On the basis of the above we conclude that the pressure sensitivity of the oscillation frequency in these experiments was primarily the result of the pressure dependence of the permittivity of the fluid surrounding the FET, rather than being the result of changes in the characteristics of the transistor itself. In its present configuration, the oscillator is sensitive to the permittivity of its environment because it is this permittivity that determines its output circuit capacitance. The weak dependence of frequency on gate and drain voltage means that the behavior of this device is relatively insensitive to small variations in its biasing conditions.

It should be pointed out that the pressure sensitivity and resolution achieved in these experiments are actually somewhat better than those of the familiar manganin gauge.⁹ At low pressures, where its sensitivity is highest (1.2 %/kbar), the oscillator is about 5 times more sensitive than the manganin gauge. The resolution of the oscillator at 1 kbar is 160 ppm (63 MHz measured to an accuracy of ± 0.01 MHz). For a typical manganin gauge consisting of a 100 Ω coil passing a 1 mA current, a voltage accuracy of ± 0.04 μ V would be required for similar accuracy. Even with bridge techniques an accuracy of ± 0.1 μ V is difficult to achieve, whereas a frequency measurement of the above accuracy is routine.

The results of this preliminary study suggest that common-source FET oscillators that incorporate pressure sensitive elements in their output circuits are promising candidates for sensitive pressure transducers. By incorporating lumped capacitors having a strong pressure dependence into the output stage, the pressure sensitivity could be made insensitive to the material properties of its environment and tailored to a specific application. Capacitors composed of barium titanate and strontium titanate are examples of two elements which should result in extremely high sensitivity.¹⁰

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REFERENCES

1. R. J. Chaffin, Private Communication.
2. W. Wlodarski, "Field-Effect Transistor as a Hydrostatic Pressure Transducer", Bull. Acad. Pol. Sci. Ser. Sci. Tech. (Poland), Vol. 21, pp. 743-746, Sept 1973.
3. G. A. Samara, "Pressure Dependence of the Ferroelectric Properties of Rochelle Salt", J. Phys. Chem. Solids, Vol. 26, pp. 121-125, 1965.
4. M. Maeda, K. Mimura, and H. Kodera, "Design and Performance of X-band Oscillators with GaAs Schottley-Gate Field-Effect Transistors", IEEE Trans. Microwave Theory Tech., Vol. MTT-23, pp. 661-667, Aug 1975.
5. A. Reklaitis, "Heating of Electrons in GaAs Under Hydrostatic Pressures", Sov. Phys. Semicond., Vol. 11, pp. 88-90, Jan 1977.
6. G. A. Samara, unpublished.
7. F. I. Mopsik, "Dielectric Properties of Slightly Polar Organic Liquids as a Function of Pressure, Volume, and Temperature", J. Chem. Phys., Vol. 50, pp. 2559-2569, Mar. 1969.
8. P. W. Bridgeman, Collected Experimental Papers, Vol. IV, Harvard Univ. Press, Cambridge, Mass, 1964.
9. S.E. Babb., Jr., "The Measurement of Hydrostatic Pressure", in Mechanical Behavior of Materials under Pressure. Ed: H. Pugh, Elsevier: New York, 1970, pp. 144-147.
10. G. A. Samara, private communication.

FIGURE CAPTIONS

1. The mounting of the FET on the test fixture of the pressure rig. The gate, source, and drain leads from the FET package are those shown in the 10, 2, and 4 o'clock positions, respectively. The package itself is below the ceramic chip capacitor seen in the center of the fixture.
2. Gate voltage dependence of the oscillation frequency.
 $V_d = 5 \text{ V}.$
3. Drain voltage dependence of the oscillation frequency.
 $V_g = 1 \text{ V}.$
4. Gate voltage sensitivity of the oscillation frequency as a function of drain voltage. $V_g = 1 \text{ V}.$
5. Pressure dependence of the oscillation frequency. V_g and V_d were held fixed at 1 and 5 V, respectively.
6. Comparison of the pressure sensitivity of two different devices from the same lot.
7. Pressure dependence of zero-bias conductance for both a GaAs Gunn diode and a GaAs FET.
8. Pressure dependence of the relative dielectric constant of isopentane.
9. Pressure -induced change in the capacitance across the test fixture pins.

Figure 1. The mounting of the FET on the test fixture of the pressure rig. The gate, source, and drain leads from the FET package are shown in the 10, 2, and 4 o'clock positions, respectively. The package itself is below the ceramic chip capacitor seen in the center of the fixture.

Figure 2. Gate voltage dependence of the oscillation frequency.
 $V_d = 5$ V.

Figure 3. Drain voltage dependence of the oscillation frequency.
 $V_g = 1$ V.

Figure 4. Gate voltage sensitivity of the oscillation frequency as a function of drain voltage. $V_g = 1$ V.

Figure 5. Pressure dependence of the oscillation frequency.
 V_g and V_d were held fixed at 1 and 5 V, respectively.

Figure 6. Comparison of the pressure sensitivity of two different devices from the same lot.

Figure 7. Pressure dependence of zero-bias conductance for for a GaAs Gunn diode and a GaAs FET.

RELATIVE DIELECTRIC CONSTANT

Figure 8. Pressure dependence of the relative dielectric constant of isopentane.

Figure 9. Pressure-induced change in the capacitance across the test fixture pins.

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