14p

NASA CR-138980

THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF COLLECTIVE MICROWAVE PHENOMENA IN SOLIDS

under the direction of

G. S. Kino

FINAL REPORT

for

NASA Research Grant NGL-05-020-165

National Aeronautics and Space Administration

Washington, D. C. 20546

for the period

(April 1966 through December 1972)

M. L. Report No. 2157

March 1973

Microwave Laboratory
W. W. Hansen Laboratories of Physics
Stanford University
Stanford, California

The work under this contract was initially a mixture of acoustics and Gunn effect. In recent years the work has been devoted entirely to Gunn effect.

I. MICROWAVE SHEAR WAVE STUDIES

Methods of generating microwave shear waves efficiently were studied. A new technique of mode conversion from a longitudinal wave to a shear wave was investigated and virtually 100% conversion efficiency could be obtained. New kinds of shear wave transducers using $LiNbO_3$ were devised. At the time this was a new material developed at Stanford for this purpose, among others. Conversion losses with X-cut $LiNbO_3$ disc transducers were as low as 10 dB at 1 GHz. The Bragg diffraction of light by shear waves was studied and made an excellent technique for measuring the property of the shear waves, their losses at mode converters, etc. A scheme for diffraction of shear wave column of finite width in sapphire was demonstrated, which made it possible to obtain continuous deflection of an optical beam through an angle of 4° by tuning the shear wave frequency from 1.2 to 1.8 GHz. The system was capable of resolving 1000 diffracted spots. The work resulted in a thesis by E. G. H. Lean.

A. GUNN OSCILLATOR STUDIES

Several aspects of Gunn oscillators were studied on this contract. One involved the detailed study of domains in Gunn oscillators using long samples of bulk gallium arsenide. Several new techniques were devised for measuring the properties of the domains. One involved small capacitive probes moved along the surface of the sample. A second involved applying a pulse voltage to the diode to excite a domain and then applying a second sharp pip on top of the pulse to suddenly change the width of the domain and the current passing through it. A third technique involved applying a double step in voltage to the diode to suddenly change the current through the domain. The use of these techniques enabled us to infer the amount of stored charge in the domain, the field in the domain, and the voltage across the domain. At the same time, we set up computer programs to forecast the properties of the domain in the diodes and compared our experimental results with theory.

These studies were useful and are now often referred to, to enable one to predict the circuit characteristics of an oscillator. They made it possible to determine the effective capacity of the domain, as well as its resistive characteristics and the time of buildup of a domain. Such information is required in the design of oscillators. In addition, because we had the detailed results, we were able to compare with theory and make use of this information to get some idea of the nature of the velocity-field characteristic as well as the diffusion-field characteristic of gallium arsenide — a quantity that is extremely difficult to measure accurately.

B. AVALANCHE EFFECTS

A second series of studies involving measurements of domains by the same techniques were concerned with avalanching effects in the domain. The maximum rf and dc voltages that can be applied to an oscillator are determined by the maximum field applied to the gallium arsenide. The higher the allowable rf voltage swing the greater the peak power output, and with correct design the greater the efficiency. This field is largest in the domain. When this field becomes as large as 150 - 200 kV per cm, carriers can be generated within the domain so that the maximum voltage across the device is limited by this phenomenon. A set of experiments and a detailed theory was worked out which predicted the experimental results and could predict where the onset of avalanching occurred. These results are of great help in the design of oscillators, whose maximum efficiency is limited to some extent by the maximum rf voltage swing which they can stand. This work resulted in a thesis by J. Owens.

C. STUDIES OF EFFICIENCY OF GUNN OSCILLATORS

A fundamental theory of the efficiency of a Gunn oscillator was worked out. This showed that the best rf voltage waveform to apply to a Gunn oscillator would either be a square wave or a wave the shape of a half sinusoid. Efficiencies of as great as 32% were predicted. Experiments were carried out with a square wave oscillator, using a quarter wave transmission line as a resonator, and confirmed the basic results of the theory. The theory which excited a great deal of interest in the field predicted that the use of harmonic tuning would be of great help in improving efficiency of oscillators. With just a fundamental resonator present in a sinusoidal waveform the efficiency at most would be of the order of 6 or 7%. With the addition of second or third harmonic tuning efficiencies could possibly be increased by factors of 2 or 3. More detailed computer studies on this problem have been undertaken now in several laboratories.

D. COMPUTER STUDIES OF DOMAINS

A computer program was devised to study the transient effect of domains passing through Gunn diodes. In particular, we were able to determine the properties of an oscillator in a tuned circuit driven by different kinds of current and voltage waveforms. The results enabled us to predict the impedance of an oscillator under different driving conditions.

E. EPITAXIAL GUNN OSCILLATORS

Some of the first planar epitaxial Gunn oscillators were made at Stanford. We used liquid epitaxial material grown by liquid phase techniques on semi-insulating substrate. We were able to show, even with this early material, that avalanching effects were far less severe because of the absence of traps in this material. We were able to make reasonably efficient oscillators by this technique and to show that the ratio of the peak current to the minimum current in the current waveform compared very favorably with any devices made in bulk material. At the same time, we were able to develop new techniques for making contacts to these devices.

F. THEORY OF GUNN OSCILLATORS

We developed a new theory which predicted the properties of rf signals propagating in a thin film layer of GaAs. This theory indicated that domain formation would be inhibited in thin layers of GaAs. The criterion for domain formation in a film of thickness d becomes, in this case, $nd \gtrsim 1.6 \times 10^{11}\ \mathrm{cm}^{-2}$. We were able to show in our own experiments that oscillations tended to be inhibited in thin layers of GaAs and in layers of GaAs loaded by high dielectric constant materials at the surface, as predicted by the theory. The theory was developed further and experiments carried out in a number of laboratories which agreed with the basic results of the theory.

G. GUNN AMPLIFIERS

We suggested that the growing carrier wave in GaAs when the dc field is above threshold could be used to make a traveling wave amplifier. We developed a fairly complete theory of the operation of this device, and tested out our concepts on a device made of bulk material with a resistivity in the 200-600 ohm-cm range. Most of the predictions of the theory were verified, and we were able to observe traveling wave amplification with a net gain of as much as 40 dB at L band. We were able to use this technique to determine when the gain decreased due to the effect of diffusion, and thus obtain some measure of the effect of the diffusion coefficient, normally a very difficult quantity to determine. We were also able to use this technique to determine how the gain fell off at lower frequencies, and obtain checks on our theory of wave propagation in a finite semiconductor.

We also conducted probe studies on the samples, which were typically of the order of 1 mm long, developing special capacitive and contacting tungsten probes for the purpose, and were able to measure the dc field variations along the samples. With this technique, we determined that the dc field in these samples was very uniform and in the range of negative differential mobility. This is different from what would normally be expected from theory which indicates a highly nonuniform field variation through the sample. Because in bulk material there are traps present, carriers can be ionized out of the traps, and it can be shown, as we did, that the dc field in this situation can be relatively uniform. We were able to go on and use these techniques to measure the rf phase velocity variation along the semiconductor. From these results we were able to measure the velocity-field characteristic of GaAs. This measurement was in excellent agreement with theory, and in excellent agreement with an entirely independent technique for measuring the velocity-field characteristic which we had developed in this laboratory. This work and the work on the bulk amplifier resulted in a thesis by B. Fay.

We then carried out a detailed theory of wave propagation in thin films, with the intention of making an epitaxial Gunn amplifier at X band. The theory predicted that we should be able to make relatively low impedance devices with an FET configuration which would give large, broadband traveling wave gains at X band.

In our experiments we have seen evidence that such gain is there. But we have had a great deal of difficulty with the technology required. The devices required material with a resistivity of a few ohm-cm, and a few microns thick laid down on a semi-insulating substrate. Such material is difficult to make and it is also difficult to make contacts to it. Our experiments were initially encouraging. We were able to make devices in which we could vary the ratio of the output to the input by varying the potential across them, but we were never confident that the dc fields were as predicted because of the problem with contacts and the problem of uniformity of material. There were also further problems with efficient excitation of the wave. This work resulted in a thesis by H. Weil. The work which was begun on this contract was continued on another Air Force contract.

On this contract we also carried out studies of the field variation along a layer of epitaxial material and developed a probe which was capable of determining the field variation along a sample only 50 μm long. These gave us some indication of our problems with contacts and materials, and it gave us a good check on the technology.

During this period we developed techniques for making n^+ on n contacts by epitaxial growth, GeAu contacts by alloying and In Ge Si contacts by alloying. All these techniques gave some measure of success but had problems with high resistivity and with very thin films. The n^+ on n is perhaps the most reliable but is difficult to control on samples whose dimensions are extremely small and when the distance between the gate and the ohmic contacts must be of the order of 1-5 microns. The alloyed contact can be controlled and can be etched. However, they tend to differ depending on the material on which the contacts are made at the present time.

At the present time, an FET amplifier seems to be a more viable concept because its materials requirements are not so severe. On the other hand, input-output impedance requirements and electrode spacing are more severe, but these are problems which can be dealt with by using the present technology available. As the materials technology of GaAs is developed still further, it should become easier to make Gunn amplifiers. Their advantage is broadband gain and large amounts of gain. Ideally, then, it would appear to us that the correct solution is to use an FET input to the amplifier to give low noise followed by traveling wave GaAs amplification. There are problems of controlling the uniformity of the dc field within the material, but these are viable problems, which, with the technology in hand, are soluble. Some demonstrations of GaAs amplifiers have been made elsewhere, but have been limited fairly severely by the technology. With further development, we would expect this to become a useful concept.

REPORTS ISSUED DURING THIS CONTRACT

PERIOD

M. L. Report No.	
1482	E.G.H. Lean, C.F. Quate, and H. J. Shaw, "Continuous Deflection of Laser Beams," published in Appl. Phys. Letters <u>10</u>, 2, 48-51 (15 January 1967).
1493	Staff, "Theoretical and Experimental Investigations of Collective Microwave Phenomena in Solids," Semi-annual Status Report No. 1, for 1 April to 30 September 1966 (October 1966).
1543	E.G.H. Lean, "Studies of Microwave Shear Waves in Solids," Internal Memorandum and Ph.D. dissertation (May 1967).
1546	Staff, "Theoretical and Experimental Investigations of Collective Microwave Phenomena in Solids," Semi-Annual Status Report No. 2 for 1 October 1966 to 31 March 1967 (May 1967).
1553	P. N. Robson, G. S. Kino, and B. Fay, "Two Port Microwave Amplification in Long Samples of GaAs," Published in IEEE Trans. ED, <u>ED-14</u>, 612-615 (September 1967).
1567	I. Kuru, P. N. Robson, and G. S. Kino, "Some Measurements of the Steady State and Transient Characteristics of High Field Dipole Domains in GaAs," Published in IEEE Trans. ED, <u>ED-15</u>, No. 1 (January 1968).
1599	Staff, "Theoretical and Experimental Investigations of Collective Microwave Phenomena in Solids," Semi-annual Status Report No. 3 for 1 April to 30 September 1967 (November 1967).
1643	Staff, "Theoretical and Experimental Investigations of Collective Microwave Phenomena in Solids," Semi-annual Status Report No. 4 for 1 October 1967 to 31 March 1968 (May 1968).
1689	G. S. Kino and I. Kuru, "High-Efficiency Operation of a Gunn Oscillator in the Domain Mode," Published in IEEE Trans. on Electron Devices, <u>ED-16</u>, 9, 735-748 (September 1969).

M. L. Report No.

1695	Staff, "Theoretical and Experimental Investigations of Collective Microwave Phenomena in Solids," Semi-annual Status Report No. 5 for 1 April to 30 September 1968 (October 1968).
1744	Staff, "Theoretical and Experimental Investigations of Collective Microwave Phenomena in Solids," Semi-annual Status Report No. 6 for the period 1 October 1968 to 31 March 1969 (April 1969).
1751	G. S. Kino and P. N. Robson, "The Effect of Small Transverse Dimensions on the Operation of Gunn Devices," Published in Proc. IEEE 56, 11, 2056-2057 (November 1969).
1789	B. Fay and G. S. Kino, "A New Measurement of the Velocity-Field Characteristic of GaAs," Published in Appl. Phys. Letters 15, 10, 337-339 (15 November 1969).
1807	Staff, "Theoretical and Experimental Investigations of Collective Microwave Phenomena in Solids," Semi-annual Status Report No. 7 for 1 April to 30 September 1969 (October 1969).
1823	Staff, "Theoretical and Experimental Investigations of Collective Microwave Phenomena in Solids," Semi-annual Status Report No. 8 for 1 October 1969 to 31 December 1969 (January 1970).
1850	Staff, "Theoretical and Experimental Investigations of Collective Microwave Phenomena in Solids," Semi-annual Status Report No. 9 for 1 January to 31 March 1970 (April 1970).
1895	Staff, "Theoretical and Experimental Investigations of Collective Microwave Phenomena in Solids," Semiannual Status Report No. 10 for 1 April to 30 September 1970 (October 1970).
1908	B. Fay, "A Two-Port Unilateral Gallium Arsenide Amplifier," Internal Memorandum and Ph.D. dissertation (August 1970).
1920	J. A. Higgins, "Amplification and Oscillation in Liquid Phase Grown Epitaxial Gallium Arsenide," Internal Memorandum and Ph.D. dissertation (December 1970).

M. L. Report No.

1945	Staff, "Theoretical and Experimental Investigations of Collective Microwave Phenomena in Solids," Quarterly Status Report No. 11 for 1 October 1970 to 31 December 1970 (March 1971).
1958	Staff, "Theoretical and Experimental Investigations of Collective Microwave Phenomena in Solids," Quarterly Status Report No. 12 for 1 January to 31 March 1971 (April 1971) .
1990	Staff, "Theoretical and Experimental Investigations of Collective Microwave Phenomena in Solids," Quarterly Status Report No. 13 for 1 April to 30 June 1971 (August 1971).
----	H. M. Weil, "Space Charge Wave Amplification in Thin GaAs Films," Ph.D. dissertation (May 1971).
2023	Staff, "Theoretical and Experimental Investigations of Collective Microwave Phenomena in Solids," Quarterly Status Report No. 14 for the period 1 July to 30 September 1971 (November 1971).
2028	M. Bini and G. R. Bisio, "The Effect of the Non-uniform dc Field on Carrier Waves in Negative Differential Mobility Semiconductors," Published in Appl. Phys. Letters 20, 3 (1 February 1972).
2048	Staff, "Theoretical and Experimental Investigations of Collective Microwave Phenomena in Solids," Quarterly Status Report No. 15 for 1 October 1971 to 31 March 1972 (April 1972).

PUBLICATION OF RELATED WORK

1690	J. Owens, "Avalanching in Gunn Oscillators," Technical Report and Ph.D. dissertation (October 1968).