June 23, 1970 J. J. SYMANSKI 3,517,336

SINGLE ELEMENT THIN FILM OSCILLATOR

Filed May 31, 1968 4 Sheets-Sheet 1

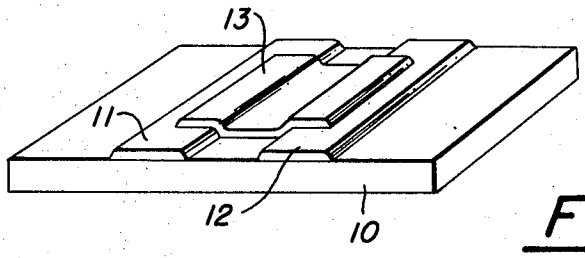


FIG. 1

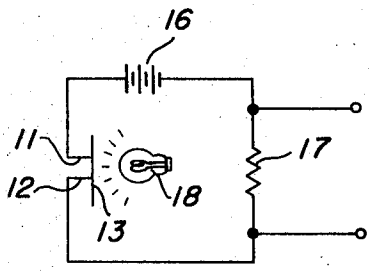


FIG. 2

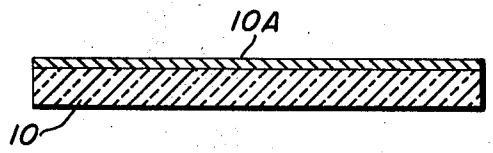


FIG. 3

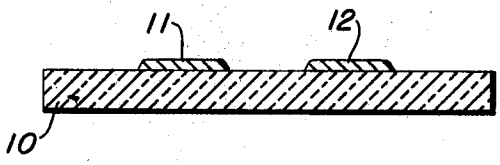


FIG. 4

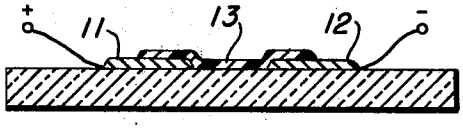


FIG. 5

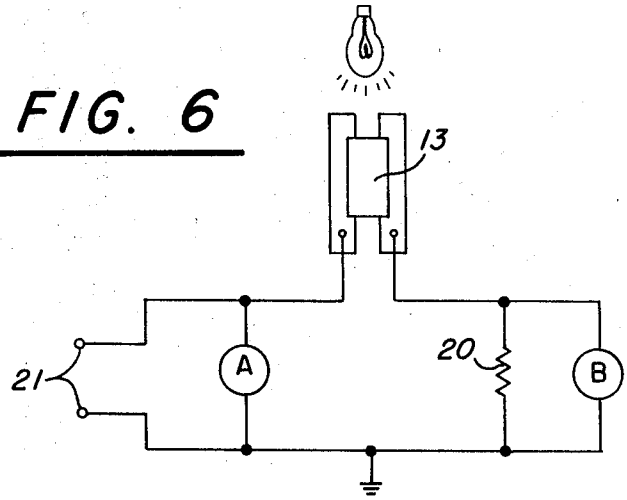
INVENTOR.
JEROME J. SYMANSKI

BY T. I. Styner
Lawrence Gilman
ATTORNEYS

SINGLE ELEMENT THIN FILM OSCILLATOR

Filed May 31, 1968 4 Sheets-Sheet 2

FIG. 6



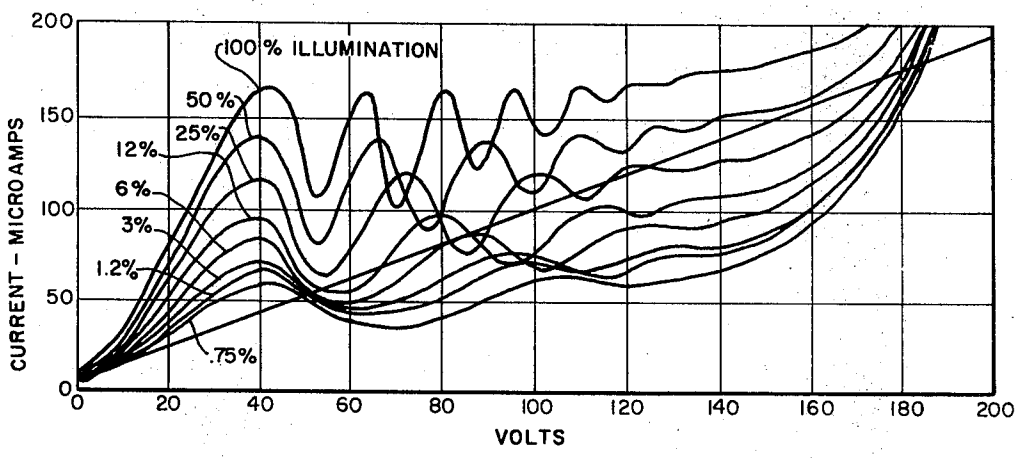


FIG. 7

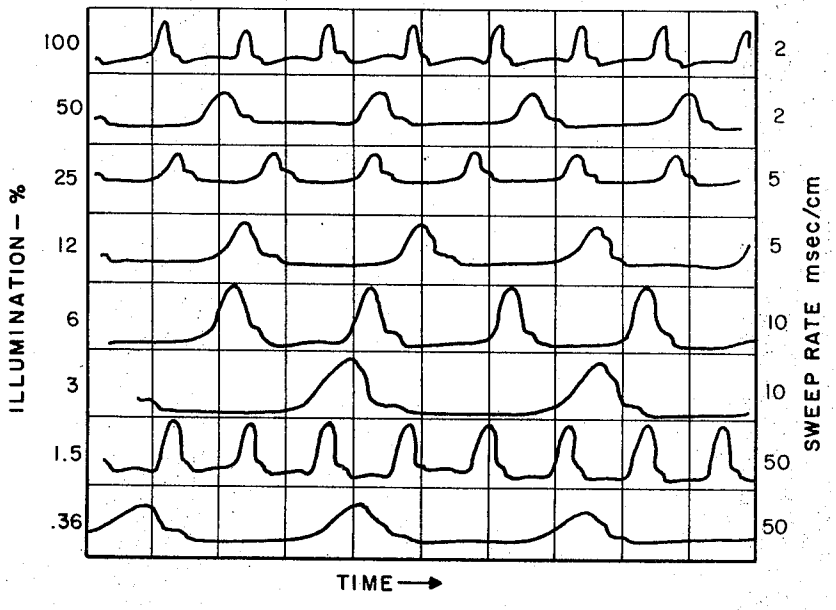
INVENTOR.
JEROME J. SYMANSKI
BY
ATTORNEYS

June 23, 1970 J. J. SYMANSKI 3,517,336

SINGLE ELEMENT THIN FILM OSCILLATOR

Filed May 31, 1968 4 Sheets-Sheet 3

FIG. 8



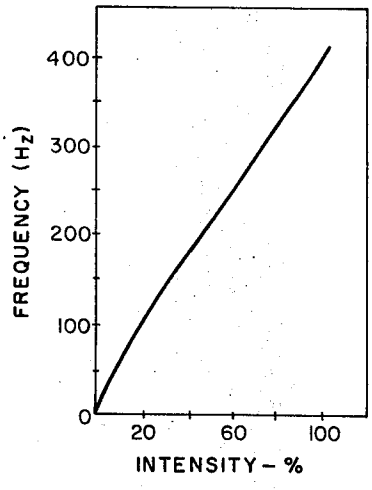


FIG. 9

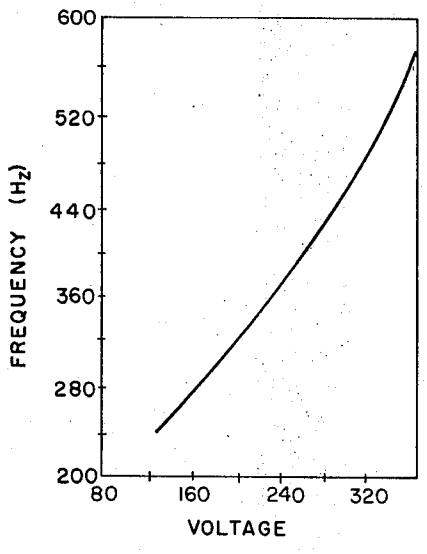


FIG. 10

INVENTOR.
JEROME J. SYMANSKI

BY T. L. Stryker
Louis D. Gibbons
ATTORNEYS

SINGLE ELEMENT THIN FILM OSCILLATOR

Filed May 31, 1968 4 Sheets-Sheet 4

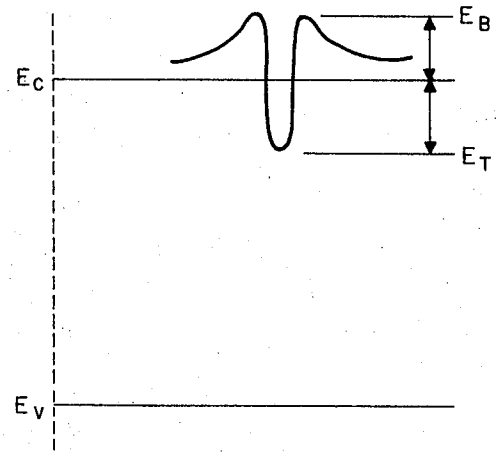


FIG. 11

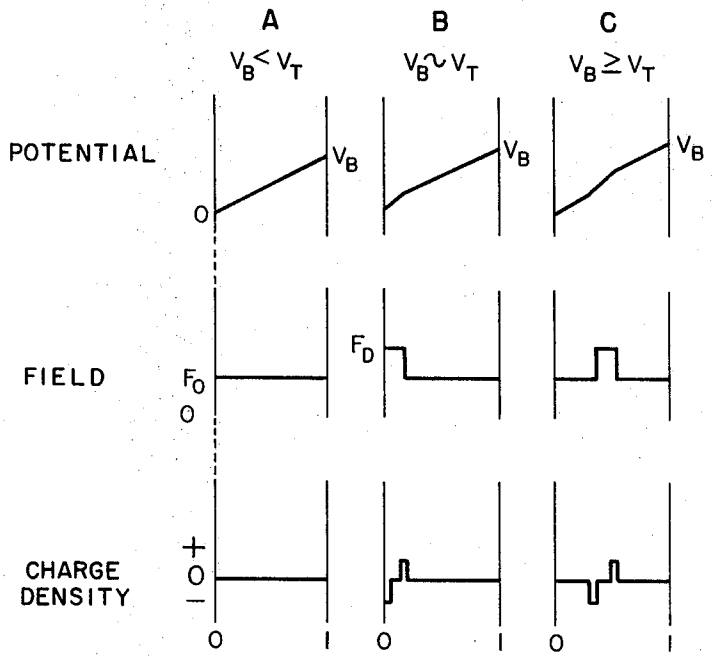


FIG. 12

INVENTOR.
JEROME J. SYMANSKI
BY
ATTORNEYS

United States Patent Office 3,517,336 Patented June 23, 1970

3,517,336

SINGLE ELEMENT THIN FILM OSCILLATOR

Jerome J. Symanski, 2928 Famosa Blvd.,
San Diego, Calif. 92107

Filed May 31, 1968, Ser. No. 733,462
Int. Cl. H03b 7/00
U.S. Cl. 331—107 4 Claims

ABSTRACT OF THE DISCLOSURE

A film of a semiconducting compound when illuminated and stressed with an electric field, is found to spontaneously and coherently generate low frequency oscillations within the semiconductor body.

The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND

The conventional oscillator is quite complex, comprising an amplifier with feedback circuits for sustaining the self imposed oscillations. A still more sophisticated oscillator comprises an evacuated electron discharge device with such fields and electrode spacings as to produce a plasma of electrons which will orbit or oscillate within the envelope as witnessed for example in the magnetron. More recently there has been observed the so-called "Gunn" effect in which a single crystal structure is used to produce extremely high frequency voltages.

SUMMARY

A thin film of seminconductor material is laid down upon a substrate and between closely spaced metal electrodes. When a voltage is applied to the electrodes and when the seminconductor is irradiated with the light from a tungsten filament, controllable frequencies under fifty kilohertz are obtainable. The frequency is a function of illumination and voltage.

The scope of this invention will be more fully understood by a reference to the preferred embodiment described in the following specification and shown in the accompanying drawing in which:

FIG. 1 is an enlarged perspective view of a semiconductor oscillator element of this invention.

FIG. 2 is the simplified wiring diagram of the oscillator of this invention.

FIGS. 3, 4, and 5 are respectively successive steps of one novel method of making the oscillator element of this invention.

FIG. 6 is a test circuit used in obtaining the characteristics of the oscillator element of this invention.

FIG. 7 shows the voltage-current characteristic of the oscillator of this invention with various levels of illumination.

FIG. 8 shows a family of waveforms for different levels of illumination with constant voltage.

FIG. 9 is a graph of the frequency versus light intensity of the oscillator of this invention.

FIG. 10 is a graph of the frequency versus voltage of the oscillator of this invention.

FIG. 11 is an energy diagram of a possible repulsive trapping site by way of explanation of the operation of the oscillator of this invention, and

FIG. 12 is a group of voltage wave forms showing sequence of domain formation and propagation of using the trapping theory of this invention.

The physical embodiment of the operative element of this invention illustrated in FIG. 1 is grossly exaggerated. Actually, the dimensions of the seminconductor can be

seen only with the aid of a microscope. The thickness of the semiconductor, for example, is measured in fractions of microns and is obtained by evaporation of the desired compounds in a vacuum as is well known in the "thin film" art.

The active element comprises an insulating base or substrate **10** such as glass, and two metal electrodes **11** and **12**. Deposited over the electrode and spanning the gap between the electrodes is a thin layer of semiconductor material **13**.

Surprisingly, coherent spontaneous oscillations occur in the seminconductor material when a voltage is applied across the electrode and the seminconductor material is illuminated by an incandescent lamp. To usefully employ the oscillator element of this invention it is merely necessary to connect the element in series with the voltage source **16**. Of course, a load impedance, **17**, must be connected in circuit with the two electrodes **11** and **12** to extract alternating currents energy. The level of illumination ample for reliable operation of one oscillator was provided by an 8-watt incandescent filament one inch from the semiconductor.

Referring specifically to FIGS. 3, 4, and 5, one novel technique of fabricating the active oscillator element of this invention is disclosed. In FIG. 3 the substrate **10** or slide of optical glass is thoroughly cleaned and is plated on one surface overall with the metal layer **10***a*. The film may be of the order of 3000 angstroms in thickness. By ordinary photo-resist techniques all of the film **10***a* is removed except the two strips **11** and **12**, shown in FIG. 4 which will now function as electrodes. The electrodes may consist of aluminum, gold, nickel, silver, or any noble or noncorrosive metal separated by a gap 10 to 250 microns wide. After the electrodes have been formed, the substrate is again cleaned and placed in the vacuum system. Semiconductor material which in one successful embodiment consists of cadmium selenide, is deposited from a high purity sintered powder obtained from Harshaw Chemical Company. The cadmium selenide was doped with from .02 to 50 parts per million of cadmium chloride. Conveniently, doping is achieved by dissolving a few milligrams of cadmium chloride in a liter of water and then adding a few microliters of this solution to the cadmium selenide. When the water had evaporated the doped powder is placed in a tantalum boat, quartz, wool plug being used to prevent spattering of the cadmium selenide during the deposition of the cadmium selenide which can be deposited at the rate of about 10 angstroms per second, while the substrate is kept at a temperature of about 175° C. After deposition, the substrate is removed from the vacuum chamber and baked for about twenty minutes at approximately 250° in room atmosphere. A film 3000 angstroms thick thus prepared shows a resistivity of about 1000 ohm centimeters.

The test circuit shown in FIG. 6 consists of the semiconductor device **13** and an appropriate resistor **20** in series with the device **13** and the adjustable voltage source connected to terminals **21**. A dual trace oscilloscope is convenient in testing device of FIG. 6, so that the voltage applied to the device in series with the resistor **20** is displayed on the A-channel while the current passing through the semiconductor **13** and the resistor **20** is displayed by monitoring the voltage across the resistor on the B-channel. For current-voltage characteristics, the linear voltage ramp generated by the oscilloscope may be employed. Alternatively, the voltage source applied to terminals **21** should be regulated and adjustable over a wide range. When sufficient illumination and direct current bias are applied to the semiconductor **13**, coherent oscillations can be seen on the oscilloscope. The illumination from a 15 watt tungsten filament light bulb, powered by a regulated direct current supply, and placed

adjustable distances, from the substrate provided ample light. Oscillations are generated at room temperature.

FIG. 7 shows the wave forms photographed on the oscilloscope screen obtained across the load resistor **20** of FIG. 6, as the voltage at **21** in changed. If, for example, the voltage out of **21** is a long voltage ramp, as shown in FIG. 7, a family of alternating waveforms may be obtained, one waveform for each level of illumination. In deriving FIG. 7, an eight watt bulb at one inch from the semi-conductor was arbitrarily assumed to be 100% illumination, and lesser amounts of illumination were applied by neutral density light filters while the linear ramp voltage was applied at **21**. With the particular oscillator of FIG. 7 it appears that the frequency of oscillation decreased as illumination decreased. This relationship of illumination to frequency is better shown in the oscillograms of FIG. 8 where a constant DC voltage is applied and different levels of illumination are applied to the semiconductor. In FIG. 8, as the frequency increased, the sweep rate in milliseconds per centimeter was increased for ease of illustration.

The oscillations occur in fields of the order of 10,000 volts per centimeter between electrodes. In most semiconductors tested there was found a narrow region of voltages near the lower threshold at which the frequency is higher than at higher voltages. The threshold oscillations are usually sinusoidal, of small amplitude and of a range in frequency from 2000 to 8000 cycles per second. As the field is increased beyond this initial region the frequency suddenly decreases to the 10 to 1000 cycle per second region, where the amplitude increases and the shape of the oscillations becomes usually quite complex. FIG. 9 shows that when the frequency is plotted as a function of the light intensity, an almost straight line results.

In FIG. 10 it appears that frequency is also nearly a linear function of applied voltage.

Several dopants have been used including cadmium chloride, $CdCl_2$, zinc chloride, $ZnCl_2$, and zinc nitrate, $Zn(CNO_3)_2$. All such salts yield semiconductors which oscillate essentially in the manner above described. The doping level can be varied widely, as much as 1 to 1000 without affecting adversely the conductivity of the semiconductor. Oscillations have also occurred in devices which were not doped at all but only baked after deposition. These devices did not behave as well as the doped devices.

THEORY

Of the possible mechanisms known that would explain the above observed phenomenon, the most likely appears to be in the field-enhanced trapping of hot electrons discussed by Ridley and Watkins in articles published by them and in vol. 78, No. 5, p. 710, 1961, in the Physical Society of London Proceedings, or in vol. 22, pp.155–158 (1961) in the Journal of Physical Chemistry. Other mechanisms such as the "Gunn" and acoustoelectric effects have much higher characteristic frequencies than those observed in the thin films of this invention. A brief, qualitative description of a model of the field enhanced trapping site and the supposed mechanism therefor is here presented in connection with FIGS. 11 and 12. Fundamental to such a model is a trapping site which has the property that its electron capture rate increases as the electric field is increased. Shallow donors and thermally excited carriers will be ignored at this point. A schematic picture of such a site is shown in FIG. 11 where the bottom of the conduction band is denoted by E_C. The trapping site has a barrier which extends an amount E_B into the conduction band. The trap level is E_T. From this picture it can be seen that only electrons which can be given energies of E_B or greater will be trapped. A possibility of tunneling through the barrier is also ignored. When a high electric field is applied, the electrons are accelerated and given more energy, raising them above the bottom edge of the conduction band, and enabling them to be trapped. Thus the unusual condition obtains that an increase in electric field causes a decrease in current, since there are fewer electrons available to act as current carriers.

Now that there is a mechanism that will cause a current drop with an increased voltage, there exists in effect, a negative resistance which is the classic condition required for generating self sustained oscillations from constant direct current power. It is merely necessary now to postulate the existence of domains or plasma or space charge clouds of trapped electrons that move between the electrodes. FIG. 12 shows at A, B, and C the sequence of events, and the relation between the applied voltage, V_B the magnitude of the electric field, F, and the charge density.

In FIG. 12A, it is assumed that the field is just below the threshold level needed to give the electron the necessary energy E_B to enter the trap. The potential across the device rises linearly, the electric field is constant and there is no space charge in the thin film semiconductor.

As the applied potential is increased to the threshold value V_T, the situation changes to FIG. 12B. Now the electrons entering the semiconductor at the cathode see a field large enough to give them sufficient energy to surmount the repulsive barrier and to be trapped. Once some of these carrier electrons have been trapped the conductivity of that region decreases and the electric field increases to F. The electrons ahead of the trapped electrons move on leaving a positive space charge or depletion region. With the formation of the high field domain, the field at the cathode drops below F_D so that the electrons entering the semiconductor are no longer trapped. Thus a group or domain of electrons with a high electric field F_O with a depletion region in front, and with an accumulation region to the rear, moves from the cathode to the anode as shown in FIG. 12C. The domain moves since conduction electrons will be heated by the domain field and then captured at the leading edge while free carriers are generated throughout the semiconductor because of the photon flux. As the domain is swept out at the anode, the electric field rises again and the process repeats.

While the foregoing model may be oversimplified, it is believed that the explanation, in view of the observed phenomenon, is plausible. The voltage and current readings and oscillograms are indisputable. A more detailed and rigorous theory, of course, may be evolved. Numerous light responsive semiconductor salts may be employed. While cadmium selenide has been mentioned, cadmium sulfide, CdS, or cadmium telluride, CdTe, may be employed when treated appropriately.

Obviously many modifications and variations of the present invention are possible in the light of the above teachings. It is therefore to be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

What is claimed is:

1. An oscillator comprising in combination;

spaced metal electrodes on and bonded to an insulating substrate,

a thin-film body of photosensitive semiconductor material formed on said substrate spanning and in good electrical contact with said spaced electrodes,

said thin-film body having a thickness of the order of 3000 angstroms throughout the space between said electrodes,

a source of radiant energy disposed to irradiate said body,

a voltage source connected across said electrodes, the voltage of said source and the level of irradiation of said body being adjusted to generate measurable coherent continuous oscillations within said body, the voltages of said oscillations appearing across said electrodes, and

output terminal means coupled to said electrodes for utilizing said oscillating voltages.

2. In the oscillator defined in claim **1**, said semiconductor material being of such composition that when

energized by said radiant energy and said voltage source, audio frequency oscillations below about 50,000 Hertz are generated.

3. The oscillator defined in claim 1 further comprising: means for adjusting the voltage level of said voltage source for adjusting the frequnecy of said oscillations.

4. The oscillator defined in claim 1 further comprising: means for adjusting the level of irradiation of said body for adjusting the frequency of oscillations.

References Cited

UNITED STATES PATENTS

3,443,103 5/1969 Lakshmanan ..... 317—235

OTHER REFERENCES

Journal of Appl. Phys. Yasukawa, pp. 3301–3303, vol. 37, No. 8, July 1966.

Journal of Appl. Phys. Kikuchi, pp. 4285–4286, vol. 37, No. 11, October 1966.

JOHN KOMINSKI, Primary Examiner

U.S. Cl. X.R.

317—235, 234; 331—66