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Another way to create negative differential resistance

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Abstract

A protocol is described for creating a diode with negative differential resistance from a semiconductor diode that initially does not have this property. This modified diode can be used as radio frequency oscillators with variable frequency to monitor change in physical properties for various organic or mineral products

Keyword :negative differential resistance , negative differential conductance ,silicon diode ,germanium diode , negistor ,parametric oscillator

Introduction

In electricity, the concept of resistance is well known. For a resistor, when the current increases, the voltage rises proportionally. For a negative resistance, it's the opposite. Many devices exhibit this characteristic; some are very old, such as the electric arc or some natural crystals like zincite. Nowadays, devices with negative differential resistance are often obtained by doping semiconductors with carefully measured foreign elements. These are then called tunnel diodes, Gunn diodes, IMPATT diodes, etc. As we will see, it is possible to impart this property to devices that initially lack it through very simple manipulations, which we will detail

Historical background

The concept of negative resistance is not new. It emerged at the end of the 19th century and quickly found practical applications. For instance, in 1893, Elihu Thomson filed a patent claiming the combination of an oscillating circuit (inductance + capacitor) with a direct current electric arc to generate an alternating current (Figure 1) (ref 1).

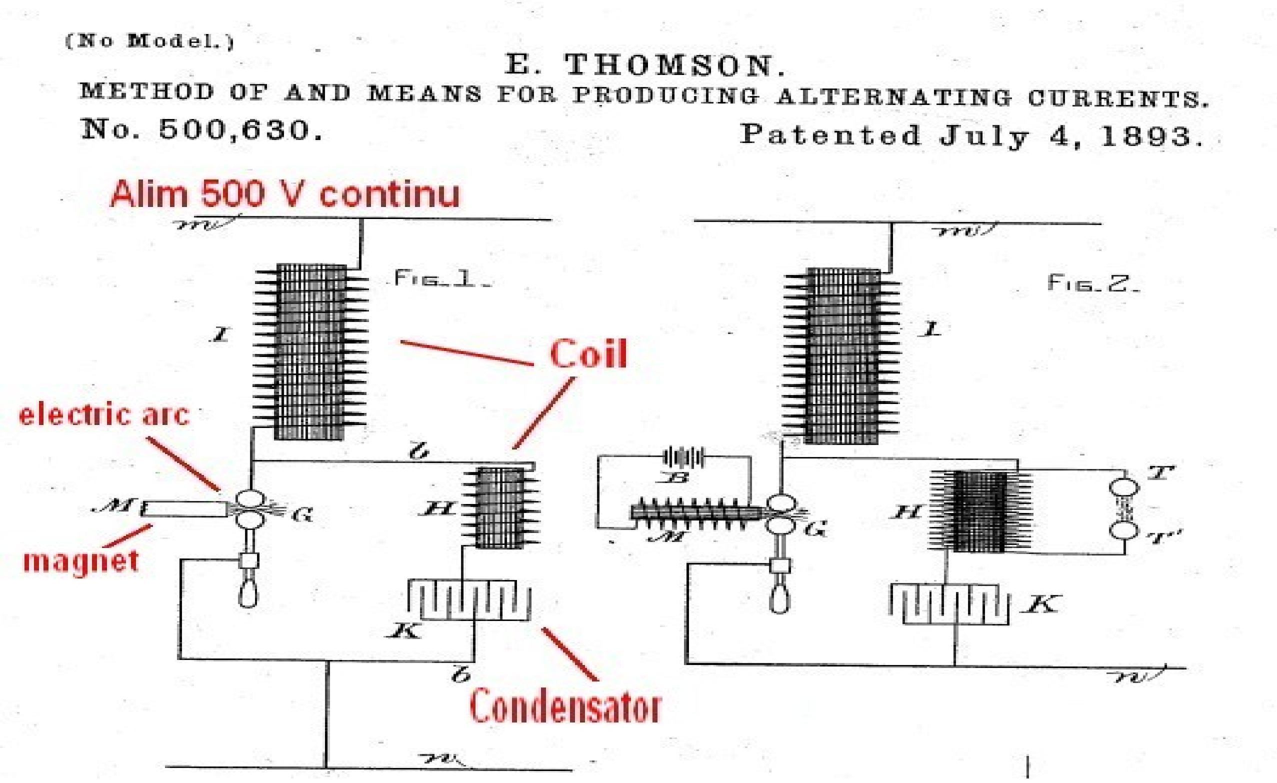
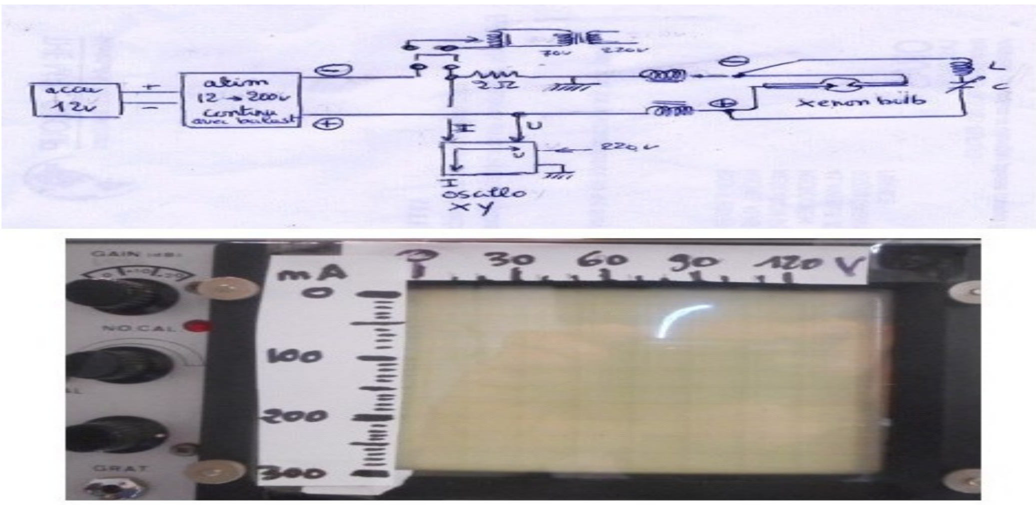


FIGURE 1 (E.Thomson Patent)

An electric arc operating in air at atmospheric pressure exhibits negative resistance in a portion of its current/voltage characteristic, which allows the L/C circuit to oscillate at its resonance frequency. The device was further developed and refined by William Duddell in 1900 (ref 2), but it was Waldemar Poulsen who made a decisive improvement by operating the arc not in air but in hydrogen or, even better, in vapors of substances that could generate it, such as ethanol (ref 3). In this way, the efficiency between the power consumed by the arc and the energy recovered in the generated alternating current was considerably improved, and the frequencies generated could reach up to several hundred kilohertz. The intended application was to create radio transmitters, and this technique quickly replaced the spark transmitters that had been used until then. This broadcasting technology lasted only about a decade, being replaced after 1920 by triode transmitters.

Measuring the negative resistance presented by an electric arc using the Poulsen technology is not easy to perform experimentally on a laboratory scale. Today, it is easier to measure the negative resistance of arcs operating in pressurized xenon. These devices are widely used in automotive lighting and, incidentally, allow for the creation of radio frequency transmitters operating at frequencies up to 1 MHz .The experimental setup is not complicated .The negative resistance appears between 70 to 90 volt with current intensity between 10 and 70 mA (Figure 2)



Xenon bulb :Negativ resisance curve

FIGURE 2 xenon bulb :negative resistance measurement

It's not just the negative resistance of the electric arc that was known at the beginning of the 20th century. It was also known that many crystals possessed this property, such as galena (lead sulfide), magnetite (iron oxide), and zincite (zinc oxide), to name a few. Measuring the negative resistance of a galena crystal when a metal electrode is applied to one of its faces is not easy; however, it is much easier to do so with magnetite crystals, which are much more stable in air

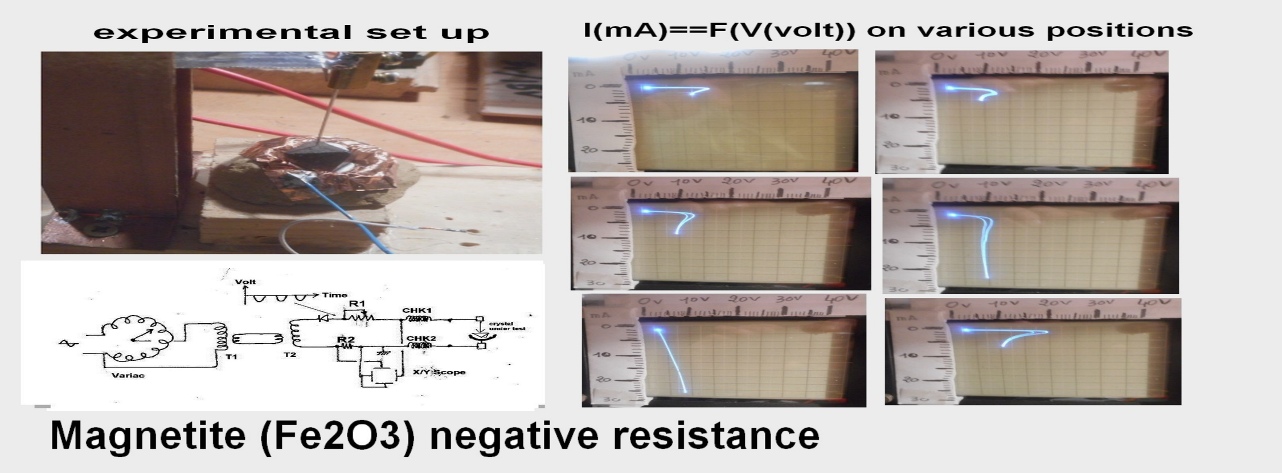


FIGURE 3 negative resistance of a magnetite crystal

When measuring the voltage across the crystal for different currents passing through it, it is observed that the voltage decreases as the current increases. This phenomenon occurs between 10 and 15 volts, depending on the position of the steel needle on the crystal's surface (Figure 3).

The specific properties of magnetite have not allowed it to achieve great success, unlike zincite (zinc oxide), which has the same characteristics. It is very easy to measure the negative resistance presented by a natural crystal of zincite (Figure 4).

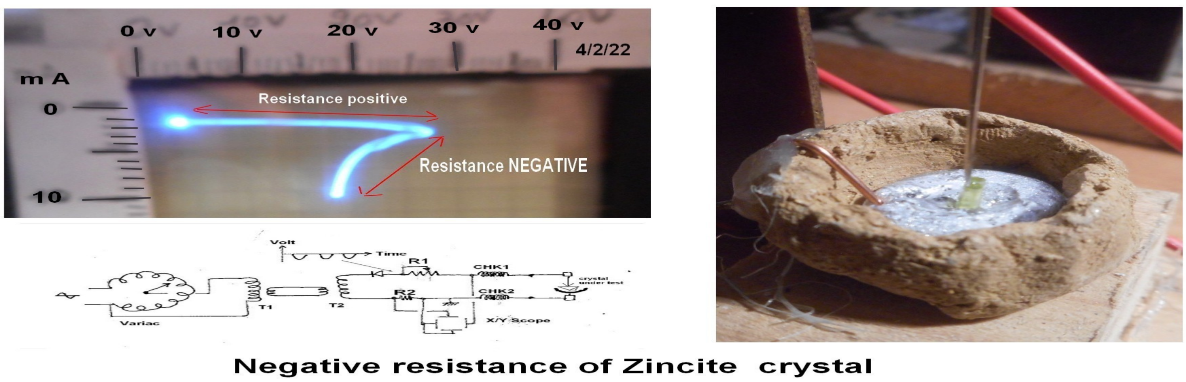
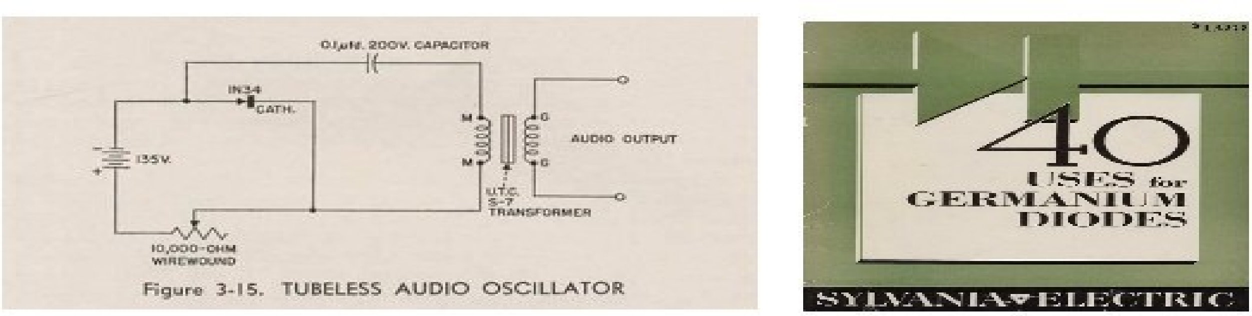


FIGURE 4 negative resistance of a zincite crystal

As shown in Figure 4, negative resistance appears starting at 26 volts, with this value varying depending on the crystal tested and the face on which the steel needle is applied. This negative resistance, associated with an oscillating circuit, was widely popularized in the 1920-1925 period through numerous articles in popular magazines by the Russian O.V. Lossev (reference 4). It should be noted that it is not necessary to use a zincite crystal to observe the phenomenon. N.M. Rust and H.J. Roud patented a method in 1925 to create this particular zinc oxide by heating galvanized iron with an electric arc (reference 5). This can also be done much more reproducibly by oxidizing a simple galvanized iron plate in the air for 2 hours at 600°C, as we have verified, to create a radio transmitter operating between 0.1 and 30 MHz with an appropriate oscillating circuit.

It is customary to consider that the starting point of negative resistance devices in modern electronics is marked by L. Esaki's foundational article ("**New phenomenon in narrow germanium P-N junction**" ref 6) in 1958, which introduced the concept of the tunnel diode. However, several years earlier, devices based on germanium diodes exhibiting negative resistance had already been mentioned in international literature. For instance, in the 1950s, the SYLVANIA company, in one of its application notes concerning its germanium diodes described an audio frequency oscillator using a 1N34 germanium point-contact diode (Figure 5).



Germanium diode 1N34 driving audio oscillator

FIGURE 5 Sylvania Application note : negative resistance of germanium diode

Some authors have patented this same application, such as William A. Miller in 1952 (ref 7).

Since Esaki's article, many other devices have been developed, including the Gunn diode and the IMPATT diode. Most of these devices share the common feature of using junctions between two different semiconductor materials, typically N-doped and P-doped, often with heavy doping. The primary application of these diodes is the creation of radio frequency generators across a wide frequency range (from kilohertz to terahertz). There are also many other devices created by stacking NP junctions, such as the negistor, which uses an NPN junction stack and was popularized in the 1970s by R. Phares (ref. 8).

In the following, we will describe another way to create a device exhibiting negative differential resistance using a semiconductor diode that does not originally have this property, and we will explain its use in generating radio frequency oscillators.

Experimental setup

Based on previous experiments, we focused on the principle of injecting sinusoidal current pulses into a reverse-biased diode, with controlled amplitude and duration. This led to the development of the setup outlined in Figure 6.

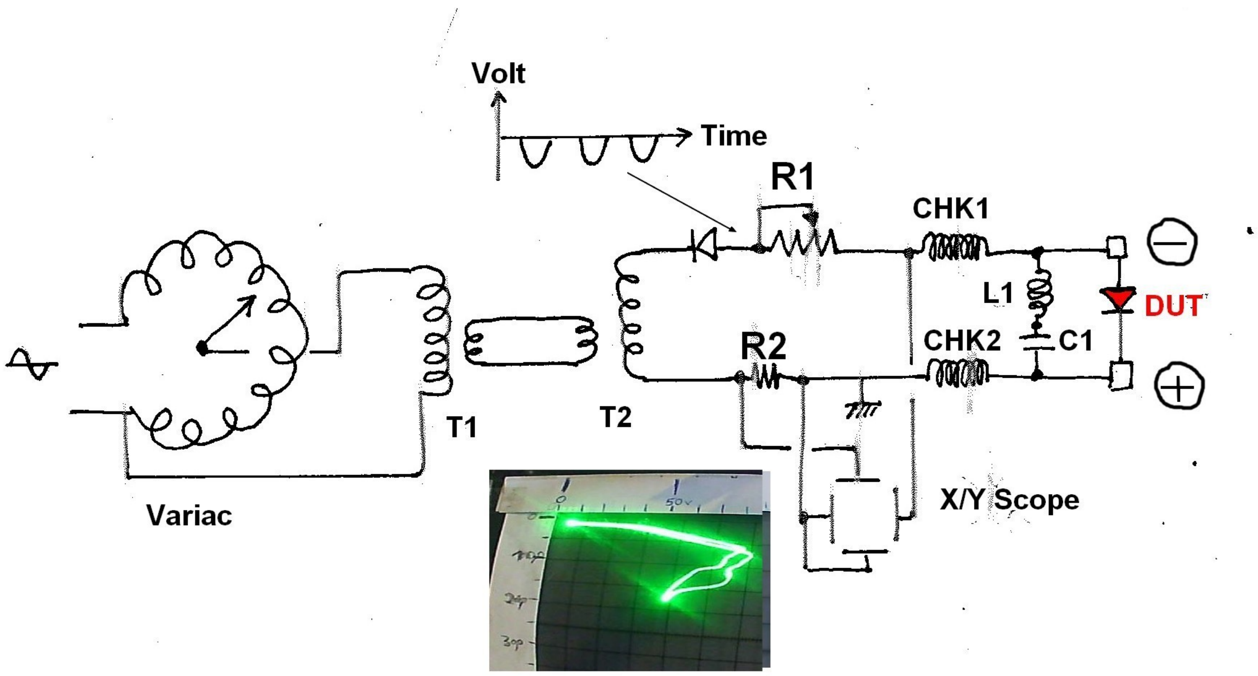


FIGURE 6 Experimental setup

A variable transformer provides an alternating voltage at 50 Hz, with one of the alternations being rectified. T1 and T2 are two identical 220V/24V transformers connected back-to-back, which also serve to galvanically isolate the circuit. Resistor R1 limits the current sent to the diode, and resistor R2 allows measurement of the current flowing through the diode under test (DUT). An oscillating circuit, consisting of an inductor L1 and capacitor C1 in parallel with the diode to be modified, completes the setup. CHK1 and CHK2 are coils that force the oscillations of the L1/C1 circuit to return to the diode. An oscilloscope allows visualization of the current passing through the diode (vertically) as a function of the applied voltage (horizontally). A camera positioned in front of the oscilloscope screen enables frame-by-frame analysis of the test, which lasts only a few seconds (analysis done using VLC software or equivalent software).

All tests were limited to the transformation of low-power commercial diodes due to limitations of experimental setup.

The maximum amplitude of the pulse (duration of 50 milliseconds) determines the temperature of the diode junction. The avalanche voltage of silicon diodes strongly depends on their temperature, as it can be easily measured on some comercially available diode (Figure 7).

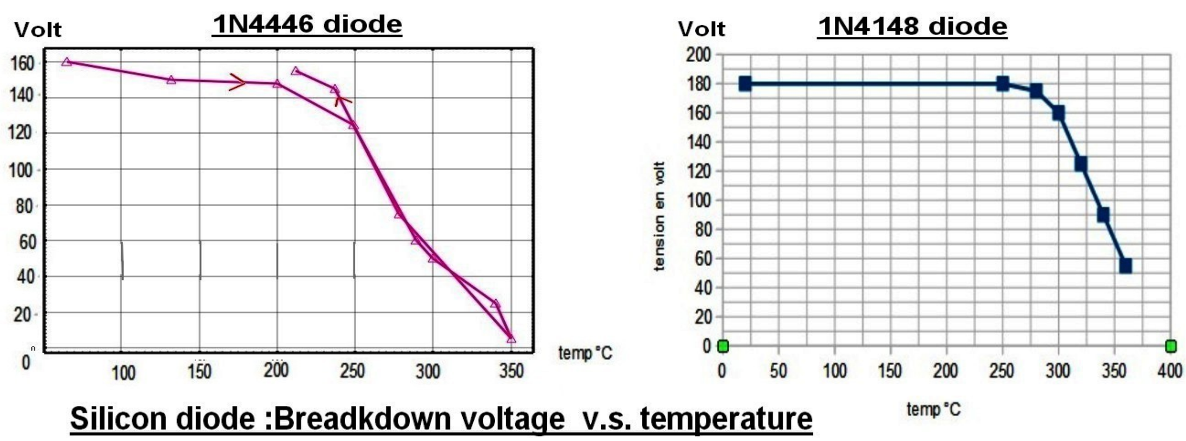


FIGURE 7 Breakdown voltage of silicon diode vs temperature

The breakdown voltage remains stable up to 250°C and drops sharply beyond that, reaching almost zero around 400°C. It is worth noting that the avalanche voltage for the same type of diode can vary significantly depending on the sample and its source. For example, with the 1N4148 diode, samples collected over a period of 10 years showed avalanche voltages ranging from 120 to 200 volts when defining the avalanche as the voltage across the diode at a fixed current of 1 mA.

The L1/C1 oscillating circuit is necessary to activate the diode under test. Its resonant frequency does not appear to be critical within the range of 200 kHz to 20 MHz. However, it is important that the quality factor of L1 ($Q = 2Pi*F*L1/R$) has to be as high as possible, meaning its ohmic resistance should be less than 2 Ohms.

The diode under test can be connected in parallel with the series oscillating circuit L1/C1. The inverse configuration is also possible: the diode in series with the L1/C1 circuit in parallel. In the latter case, it is necessary to insert a capacitor C2, which presents a low impedance at the resonant frequency of L1/C1 (Figure 8).

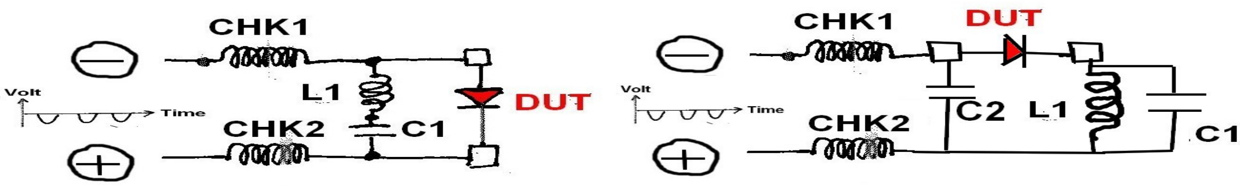


FIGURE 8 configuration of oscillating circuit : serie or parallel

Sinusoidal Pulse Activation Protocol

The diode to be activated is inserted as shown in Figure 6. The oscillating circuit in parallel with the diode resonates at 1 MHz. The current passing through the diode is gradually increased to a value specific to the diode, which is then maintained. For example, with a 1N4148 diode, the peak current is between 15 and 20 mA. Beyond this value, the avalanche voltage drops with each cycle, as observed on the oscilloscope. After a few seconds of this treatment, the diode switches, and the CURRENT/VOLTAGE characteristic on the oscilloscope displays a region of negative resistance (Figure 9). This region appears at around 50 volts, with a current between 25 and 40 mA.

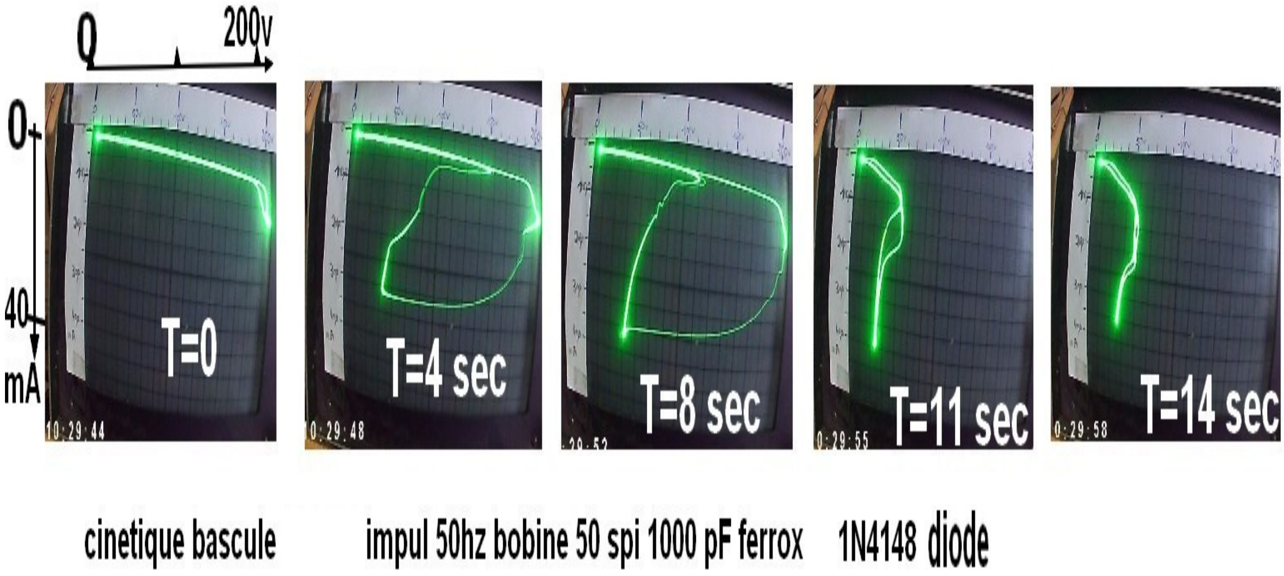


Figure 9 Activation kinetic for 1N4148 silicium diode with 50 Hz sinusoidal pulse

Simultaneously, on a radio frequency receiver tuned to the resonant frequency of the L1/C1 circuit, a carrier modulated at 50 Hz can be heard. The critical point is the peak current applied: if it is too low, nothing happens; if it is too high, the diode is destroyed. However, the stronger the current, the faster the switching occurs. Once activated, the diode can be used without limitation by biasing it within its negative resistance region, as we will see latter.

Based on the curve showing the avalanche voltage as a function of temperature, it can be determined that the diode, before switching, is subjected to peak temperatures around 350°C, 50 times per second.

The procedure was repeated on several 1N4148 diodes from the same manufacturer, giving comparable results, with notable variation, particularly concerning the value of the negative resistance obtained (Figure 10).

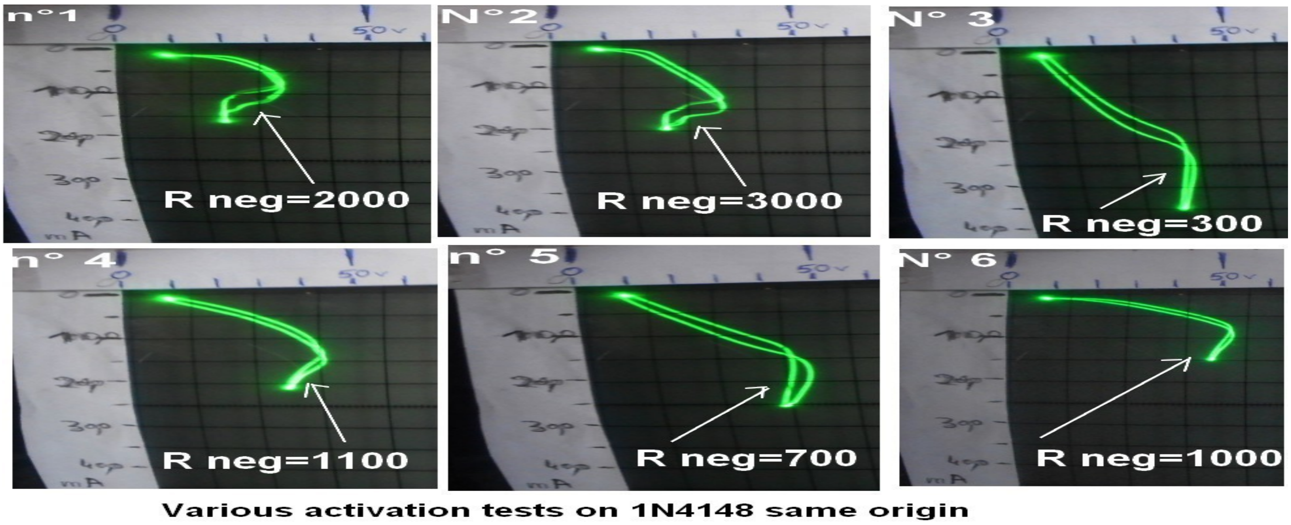


FIGURE 10: various activation tests on 1N4148 diode having same origin

This same procedure was repeated on fast-switching silicon diodes from the same family as the 1N4148. The variation in results is barely higher than that recorded on the 1N4148 (Figure 11).

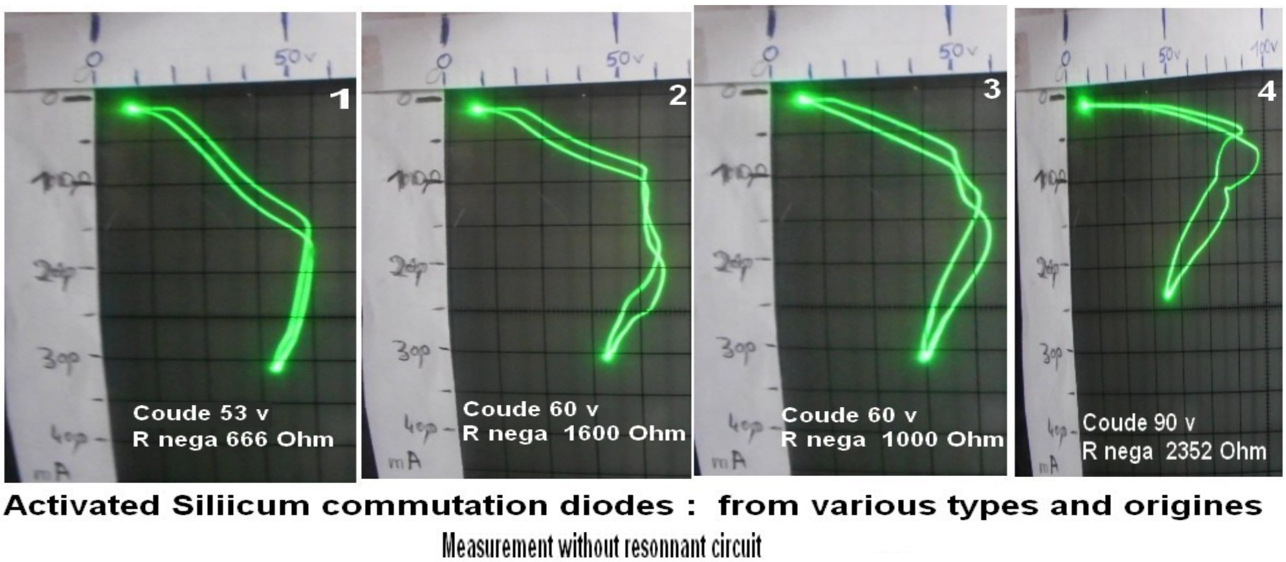


FIGURE 11 activated silicium commutation diodes , various types and origins

Negative resistance appears between 30 and 50 volts for currents between 20 and 30 mA, with the negative resistance (ΔV/ΔI) varying between 666 and 2352 ohms.

Short Pulse Activation Protocol

The idea is to reduce the pulse duration to minimize the heating of the diode. To achieve this, the setup is modified as shown in Figure 12.

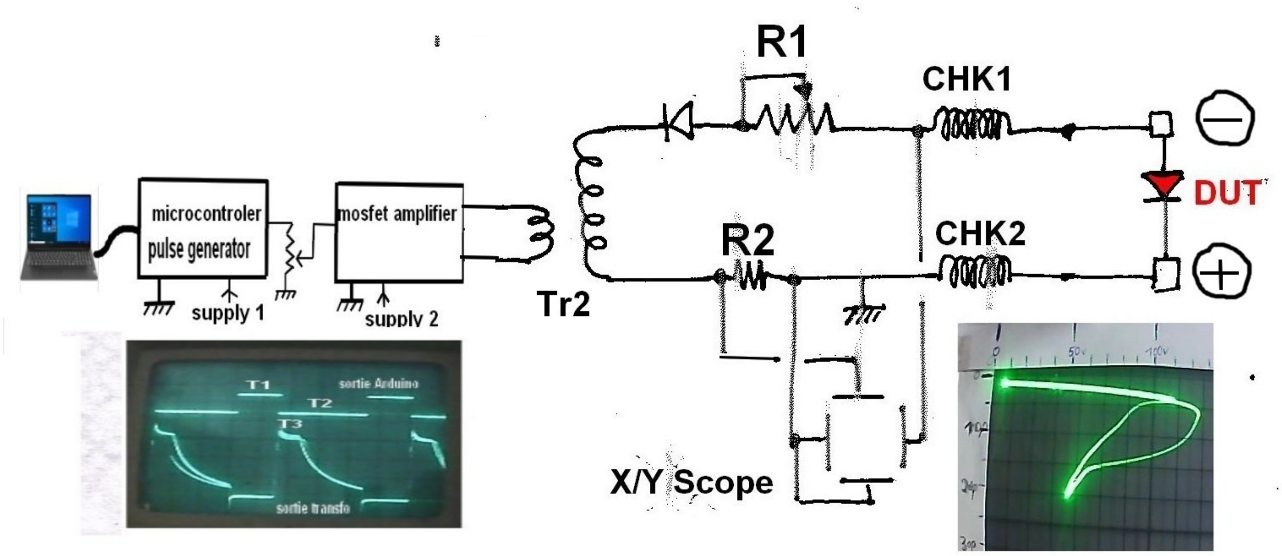


FIGURE 12: Pulse Generator with Fixed Number and Duration

A microcontroller linked to a PC generates a train of known number pulses: ON duration T1, OFF duration T2. These pulses, sent to a MOSFET amplifier, produce a series of pulses with a steep rise and exponential decay of duration T3 and a period of T1+T2. The duration T3 is proportional to T1. Tr2 is a double transformer 24V/220V (primaries in parallel, secondaries in series) that allows for the output of pulses around 600 volts unloaded, which are injected into the previously described circuit. For the tests , we have T1 = 1 millisecond, T2 = 1.4 milliseconds, and T3 = 0.4 milliseconds, and a total of 100 pulses are sent (total duration = 0.24 seconds) while recording with a camera the signals appearing on the oscilloscope (Figure 13). It should be noted that no oscillating circuit is associated with the tested diode.

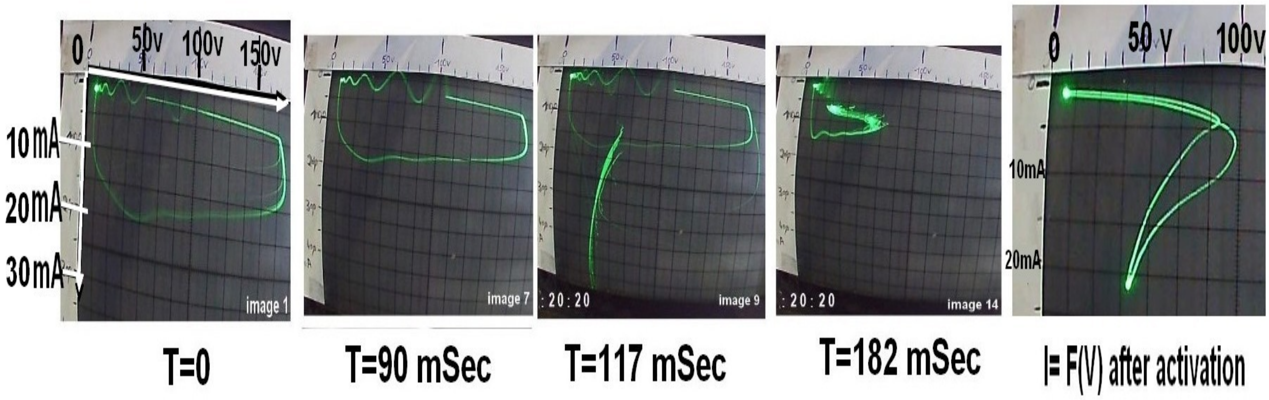


FIGURE 13: Activation kinetics of 1N4148 with 2.4 Millisecond Pulse Period

With a current pulse of 15 mA, it takes approximately 182 milliseconds, or 75 pulses, to give to the tested 1N4148 diode a new Current/Voltage curve exhibiting negative resistance between 100 and 40 volts for a current between 5 and 20 mA (negative resistance of 4000 ohms) (Figure 13). This characteristic is notably different from the one obtained by performing activation with a long sinusoidal pulse on the same type of diode (Figure 14). This characteristic remains perfectly stable as long as no oscillating circuit (L/C) is associated with it.

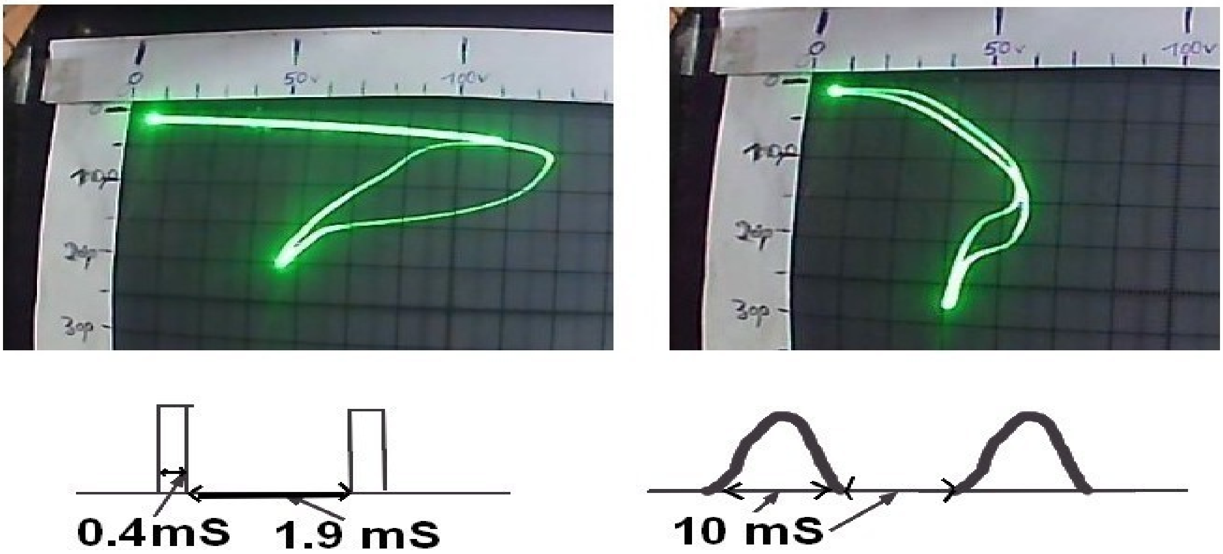
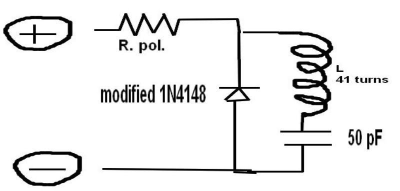


FIGURE 14 I=F(V) of activated 1N4148 depending on impulse duration

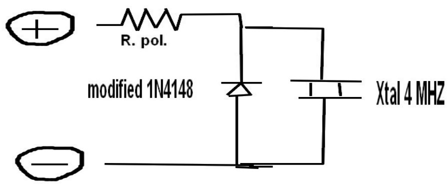
If this diode is combined with an oscillating circuit (L/C) and supplied with strictly direct current while being biased in the negative resistance region, the system oscillates at the frequency determined by the L/C circuit. However, after oscillation, the I=F(V) curve becomes similar to the one obtained with long sinusoidal pulses.

Oscillation Performance

When an activated diode is combined with an oscillating circuit, the system oscillates. The diode/oscillating circuit setup can be of either series or parallel type, as shown in Figure 8. The oscillation frequency depends on the inductance/capacitance values of the circuit. It is also slightly influenced by the current applied to the diode, except when the oscillating circuit has a high-quality factor (e.g., quartz crystal or equivalent) (Figure 15).



Voltage(V)	50	40	30
Current (mA)	15	20	25
Frequency(Khz)	3930	4350	4760



Voltage(V)	50	40	30
Current (mA)	15	20	25
Frequency(Khz)	4000	4000	4000

FIGURE 15: Oscillation Frequency Depending on Current in the Diode and Circuit Type

A simple example of a transmitter and the method for calculating the bias resistance to operate the diode in its negative resistance region are shown in Figure 16.

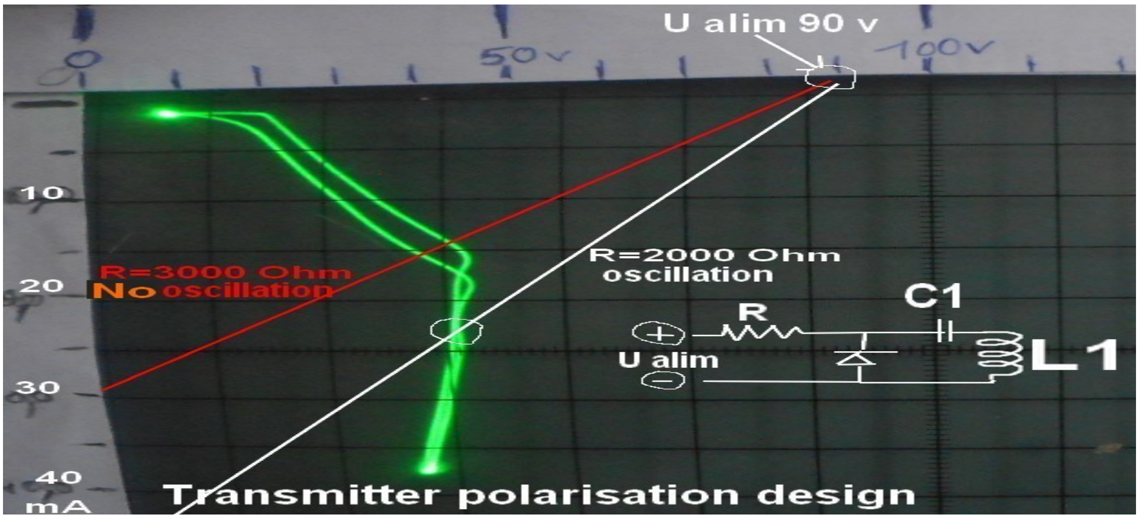


FIGURE 16 Transmitter bias resistance calculation

By appropriately selecting the values of L1 and C1, it is possible to transmit between 100 kHz and 80 MHz using an activated 1N4148 diode. A simple implementation of a radio transmitter operating in the AM band involves using L1 with 80 turns of wire wound on a 1 cm diameter ferrite core, and C1 with a capacitance of 1000 pF. Reception is done using a commercially available receiver, with frequency adjustment achieved by sliding the core within the coil.

Activation of transistor junction

The procedures described earlier have been tested on silicon junction diodes. They can also be used to modify the junctions of transistors and other types of diodes.

Silicon NPN transistors are known to exhibit a negative resistance between the EMITTER and COLLECTOR. This can be easily measured using a 2N2222 transistor as an example (Figure 17).

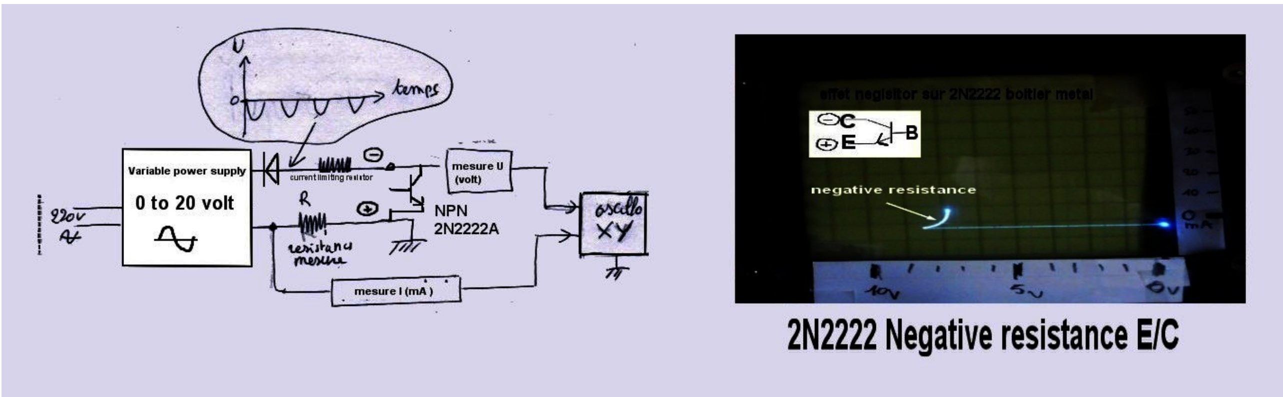
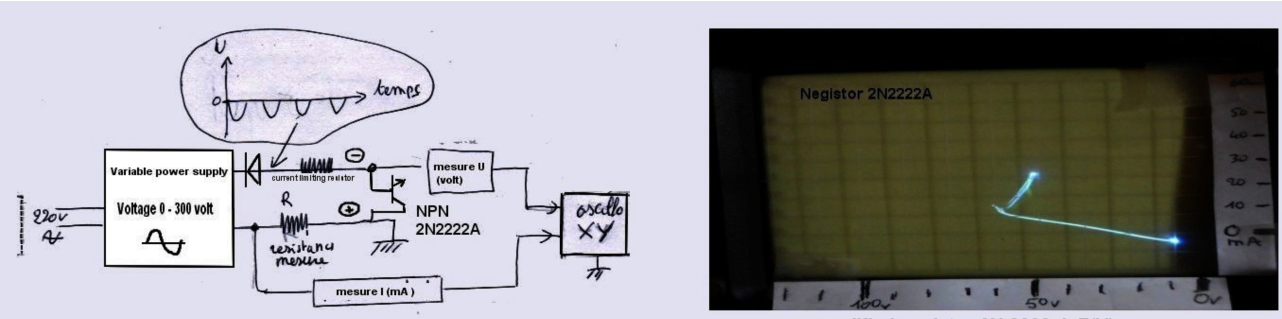


FIGURE 17 Negative resistance between E/C for 2N 2222 tansistor

With the sample used, the negative resistance is observed between 7.5 V and 8.5 V for a current of approximately 0 to 10 mA.

If this transistor is subjected to activation of its BASE/COLLECTOR junction by a controlled current injected into this junction operating in reverse bias (BASE connected to the negative pole, COLLECTOR to the positive pole, as in the case of an NPN transistor) as previously described (Figure 6), the junction exhibits a negative resistance between 50 and 60 V for currents between 10 and 20 mA (Figure 18).

Repeating this activation on other 2N2222 transistors from the same manufacturer yields very similar curves. Interestingly, some of the transistors modified in this way at their Emitter/Base junctions continue to retain their amplifying properties, but most lose these properties and behave equivalently to two back-to-back diodes.

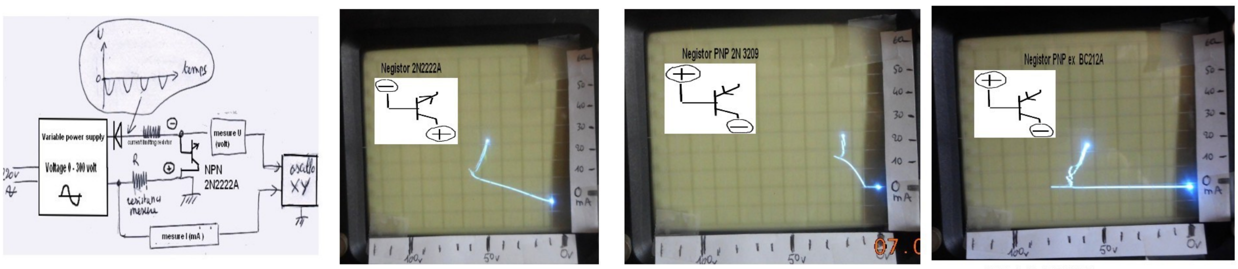


modified negistor 2N 2222 I=F(V)

FIGURE 18 Negative resistance of 2N2222 BASE/EMITTER junction after activation

By connecting an oscillating circuit to the BASE/EMITTER junction and biasing it within its negative resistance region, an alternating signal can be generated, with a frequency that can reach up to approximately 80 MHz.

Repeating the activation on different types of low-power silicon switching transistors can also impart a negative resistance to their base/emitter junction, though with significant variations (Figure 19).



NPN 2N2222 PNP 2N3209 PNP BC212A

FIGURE 19 : Negative resistance of Base/Emitter junction for various silicium transistors

The procedure also works on germanium transistors of the same category. An activation test was conducted on a germanium PNP transistor (reference AFxxx) by sending pulses to the Base/Collector junction in reverse bias, with an oscillating circuit in parallel. It is necessary to extend the treatment for several tens of seconds to achieve a stable negative resistance (Figure 20).

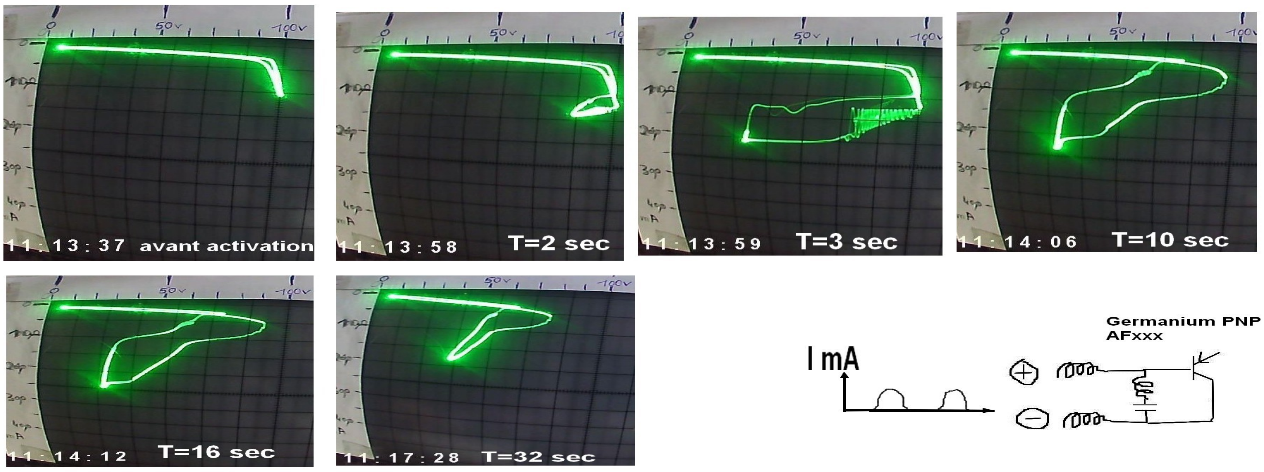


FIGURE 20 Activation of Base/Emitter junction for germanium transistor AFxxx

Activation of Other Junctions

An interesting case is the activation of metal/semiconductor junctions, such as those found in Schottky diodes. As an example, the BAT41 diode (a silicon diode) was used, which has an avalanche voltage of approximately 190 volts.

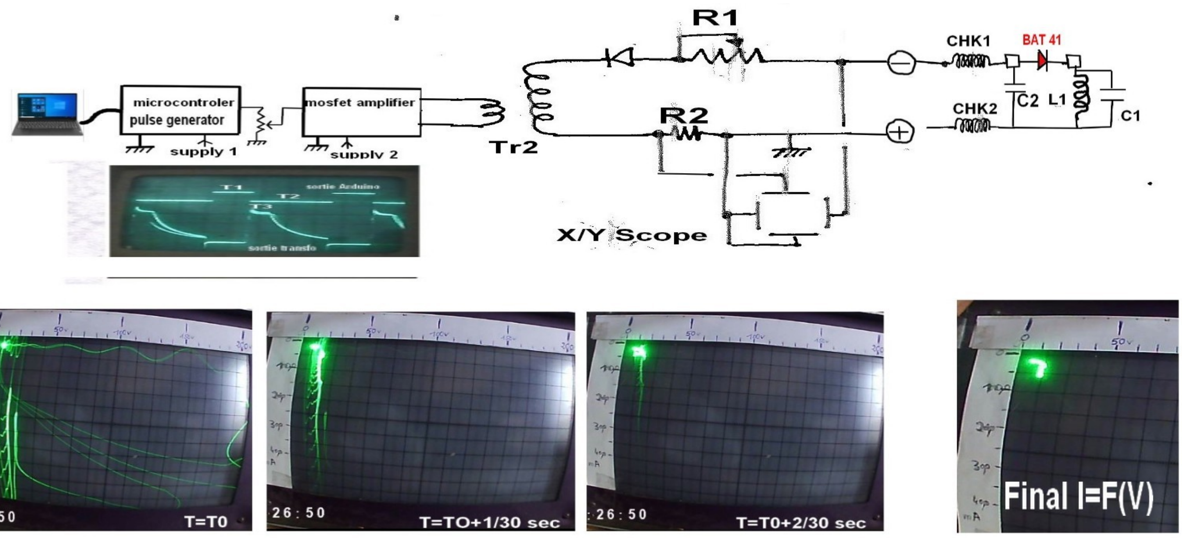


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FIGURE 21 activation for Schottky diode BAT 41

The activation is carried out according to the setup described in Figure 21 by sending a pulse train of current (Imax approximately 30 mA) with a duration of 0.4 milliseconds (T3), followed by a waiting period of 1.9 milliseconds (T2). The diode switches in less than 1/30th of a second and, after the treatment, exhibits negative resistance starting from 10 volts for currents ranging from 0 to 8 mA (Figure 21, FINAL I=F(V)). When this diode is connected to an oscillating circuit and biased within its negative resistance region, it enables the circuit to oscillate.

Conflicts of interest

There are no conflicts to declare

Availability of data and materials

All data and materials are avavailable on request at the author email or at alas@microchem.fr

Competing interests

There are no competing interests to declare

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