Negative resistance oscillators

Considering the amount of attention given to *superconducting* materials which have an effective electrical resistance of zero it is surprising that the property usually called *Negative Resistance* is so little known. Yet devices and systems exploiting this effect are widely used to make amplifiers and oscillators in the microwave, mm-wave and Terahertz frequency range which lies between conventional electronics and infra-red optics. Many materials and devices exhibit negative resistance — *IMPATT* diodes, Multiple Quantum Well's, etc. Here we will use the example of the *Gunn* effect, named after its discoverer. Figure illustrates the *I/V Curve* of a suitable piece of semiconductor material. This shows how the current through the material varies with the voltage applied across it. Various sorts of semiconductor show this effect, but the types used most often for commercial purposes are GaAs and InP.

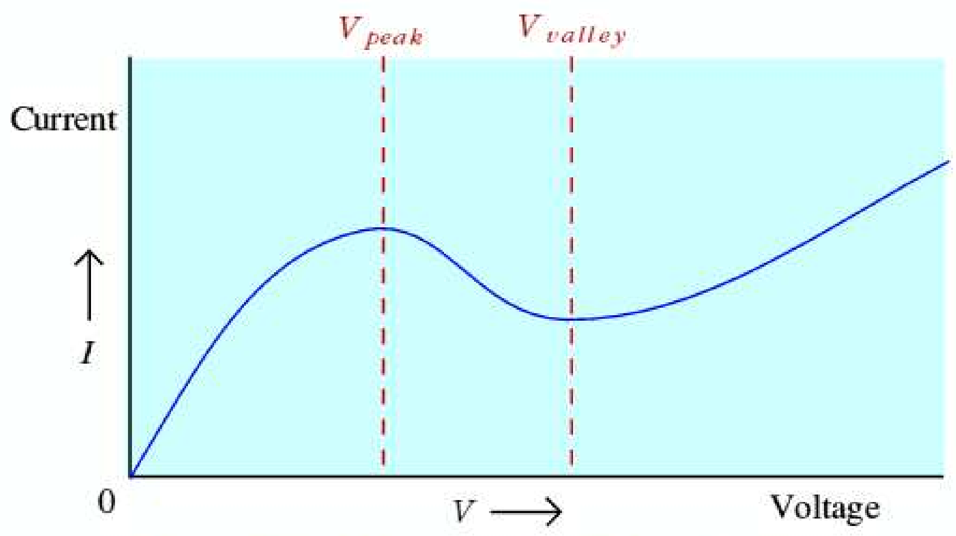


Figure 5.1 I/V curve of a Gunn diode.

A *Gunn Diode* is essentially just a piece of doped semiconductor with two electrical contacts on opposite ends. (In reality, most Gunn Diodes are more complex than this to make them work better, but these details don't matter here.) Its called a "diode" because it has just two wires and has a *non-linear* I/V behaviour like normal diodes. However, unlike 'real' diodes its I/V behaviour is symmetric — i.e. if a voltage, *V*, gives a current, *I*, then a voltage, $-V$, will give a current, $-I$.

There are two ways to define the resistance of a device or piece of material. In most circumstances we use the *Static Resistance*,

$$R \equiv V / I \qquad \text{... (5.1)}$$

but we can also define the *Dynamic* (or *Differential*) *Resistance*

$$r \equiv \frac{dV}{dI} \qquad \text{... (5.2)}$$

For most materials the current is simply proportional to the applied voltage and these two ways of specifying resistance are indistinguishable. Such materials are said to obey *Ohm's Law*. Looking at the *I/V* plot illustrated in figure 5.1 we can see that this material is <u>not</u> *Ohmic*. In general, the current tends to rise with increasing voltage, but there is a region between the *peak voltage*, V_{peak} , and *valley voltage*, V_{valley}, where the the current <u>falls</u> as the voltage is increased. This is called the *Negative Resistance Region* because in this voltage range the dynamic resistance, $r < 0$. Note, however, that the static resistance is always positive. For this reason, although it is conventional to call this effect 'negative resistance' it should more strictly be called *Negative Differential Resistance* or *Negative Differential Conductance.* The peak voltage is often called the *Threshold* voltage since it represents a threshold we have get over to reach the negative resistance region.

The usefulness of negative resistance can be understood by considering the circuits shown in figure 5.2. Fig 5.2a shows a standard series resonant *RLC* arrangement. Using a.c. circuit analysis we can say that the total voltage around the *RLC* loop will be

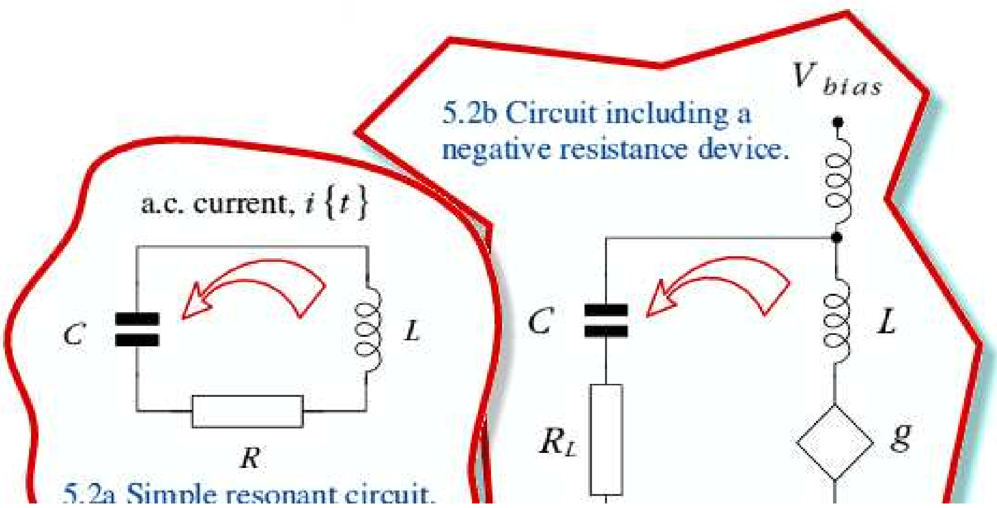
$$0 = \frac{di\{t\}}{dt}L + i\{t\}R + \int \frac{i\{t\}}{C}\,dt \qquad \text{... (5.3)}$$

This equation can be solved to obtain the result that the current around the loop must be of the general form

$$i\{t\} = \mathrm{Exp}\{At\} \qquad \text{... (5.4)}$$

where

$$A = \frac{-R \pm \sqrt{R^2 - 4L/C}}{2L} \qquad \text{... (5.5)}$$



5.2b Circuit including a negative resistance device.

5.2a Simple resonant circuit.

Figure 5.2 Negative resistance oscillator.

Here we will concentrate on what happens when $R^2 < 4L/C$. When this condition is satisfied the part of expression 5.5 inside the root is negative and hence *A* is complex. We can then say that the current variations will take the form

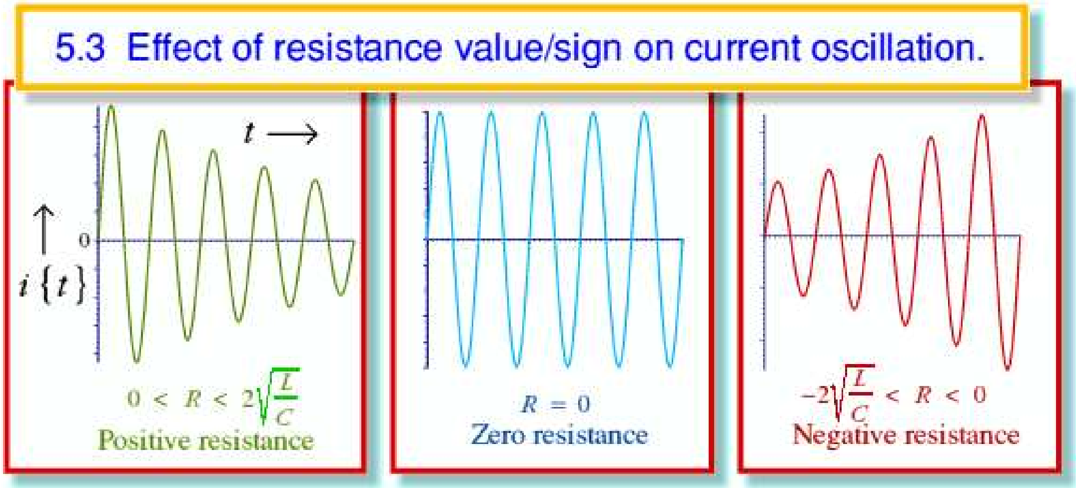
$$i\{t\} = \mathrm{Exp}\{\alpha t\}\,\mathrm{Exp}\{i\omega t\} \qquad \text{... (5.6)}$$

where

$$\alpha = \frac{-R}{2L} \quad ; \quad \omega = \left|\frac{\left|\sqrt{R^2 - 4L/C}\right|}{2L}\right| \qquad \text{... (5.7)}$$

Figure 5.3 illustrates how the current in the circuit varies with time when we start with an initial non-zero current, $i\{0\}$. In each case the current can be see to oscillate sinusoidally with the angular frequency, ω, and the amplitude of the oscillation varies exponentially with time in a way which depends upon the resistance.

In most situations the circuit resistance will have a positive value. This means that α is negative and the oscillation's amplitude declines exponentially as time passes. In effect, the circuit starts with an amount of energy stored in the inductance by the starting current, $i\{0\}$. As time passes this energy is dissipated by the resistor. The oscillation energy fades away and the resistor warms up. However, if we can arrange for the resistance to be zero, the initial current starts an oscillation whose amplitude remains unchanged as time passes. None of the oscillation energy is ever dissipated.



5.3 Effect of resistance value/sign on current oscillation.

A negative resistance value means that α is positive. This means the oscillation amplitude and energy grow exponentially with time. In practice, we can't ever obtain an oscillation whose energy grows larger without limit. Infinite powers and energies aren't accessible in the real world! Something always restricts the rate at which the system can 'create' oscillation power. Fairly obviously, this power must also come from somewhere!

Content and pages maintained by: Jim Lesurf (jcgl@st-and.ac.uk)
using TechWriter Pro and HTMLEdit on a StrongARM powered RISCOS machine.
University of St. Andrews, St Andrews, Fife KY16 9SS, Scotland.