Stability of a reflective coupling diode with the inclusion of thermal effects in narrow band-gap materials

M J Gilbert, R Akis and D K Ferry

Department of Electrical Engineering and Center for Solid State Electronics Research,
Arizona State University, Tempe, AZ 85287-5706, USA

Abstract
Despite the difficulty in fabrication, resonant tunnelling diodes (RTD) have
found a great deal of usage in the analogue, digital and mixed signal realms
as a means of increasing the speed of signal processing circuitry, or in
reducing the static power dissipation in the circuitry. Nevertheless, RTDs
suffer from their non-planar structure. One possible solution is a planar
diode, which operates via coupling of injected electron modes from an input
waveguide to a corresponding output waveguide in a semiconductor
hetrostructure, or a reflective coupling diode (RCD). In this paper, we
investigate the role of temperature on the operation of an RCD.

The resonant tunnelling diode (RTD) has been a staple of physics for many years. It has found great many uses in analogue, digital and mixed signal circuits [1]. However, the fact that the RTD must be fabricated using molecular beam epitaxy (MBE), which results in a non-planar device, leads to some drawbacks. First, the traditional RTD must be grown in layers with precise control over the application of different layers of atoms to form the device. If precise control of the location and thicknesses of atomic layers is lost, then the operation of the device could change significantly as the barriers change size and shape. These changes in the size and shape of the quantum well will accordingly alter the position and the form of the $I-V$ characteristics. While the science of MBE has reduced the probability of losing precise control of the atoms that impinge on a given substrate to form the RTD, this has not erased the problem of melding a non-planar device into a planar integrated circuit. Therefore, efforts have been made to explore the possibility of using other quantum phenomenon to induce similar $I-V$ characteristics as those seen in the RTD [2–6]. To this end, there has been a recent proposal of a single input, single output device fabricated in a coupled waveguide structure, the reflective coupling diode (RCD) [7]. The RCD operates based on the fact that in a coupled waveguide structure there exits highly reflective energies where the incident modes are reflected back to the input of the device, thereby producing similar $I-V$ characteristics as that of the RTD. In this paper, we study the effects that

temperature and material disorder have on the operation of the RCD.

The structure under consideration is described in [7]. The simulations are performed on a discretized grid using a variation of the Usuki mode matching technique via the scattering matrix [8], using a grid spacing of 5 nm. To examine the effects of finite temperature on the system, we must include the difference between the Fermi level at the source and the Fermi level at the drain in the Landauer formula, as well as include the thermal effects on the energy of the incoming mode. To include thermal effects we now use

$$I(V_{sd}) = \frac{2e}{h} \int dE \cdot T(E) \left[f_s(E) - f_d(E - eV_{sd}) \right] \quad (1)$$

to calculate the current at different applied biases where, in the above equation f_s and f_d are the values of the Fermi functions at the source contact and drain contacts, respectively.

In figure 1, we plot the $I-V$ characteristics of the RCD with the inclusion of thermal effects. In figure 1(*a*), we plot the $I-V$ characteristics of the RCD with no thermal effects included and the source–drain bias varied from 0–3 mV. This causes a spatial modulation of the Fermi level in the system, which in turn, causes a modulation of the velocity of the incoming mode. In figure 1(*b*), we plot the $I-V$ characteristics of the RCD with the temperature of the system set to 1 K. In figure 1(*b*), we note several differences from the ideal case. First, we note that magnitude of the current has been reduced. This can be explained by the fact that now, when the Landauer
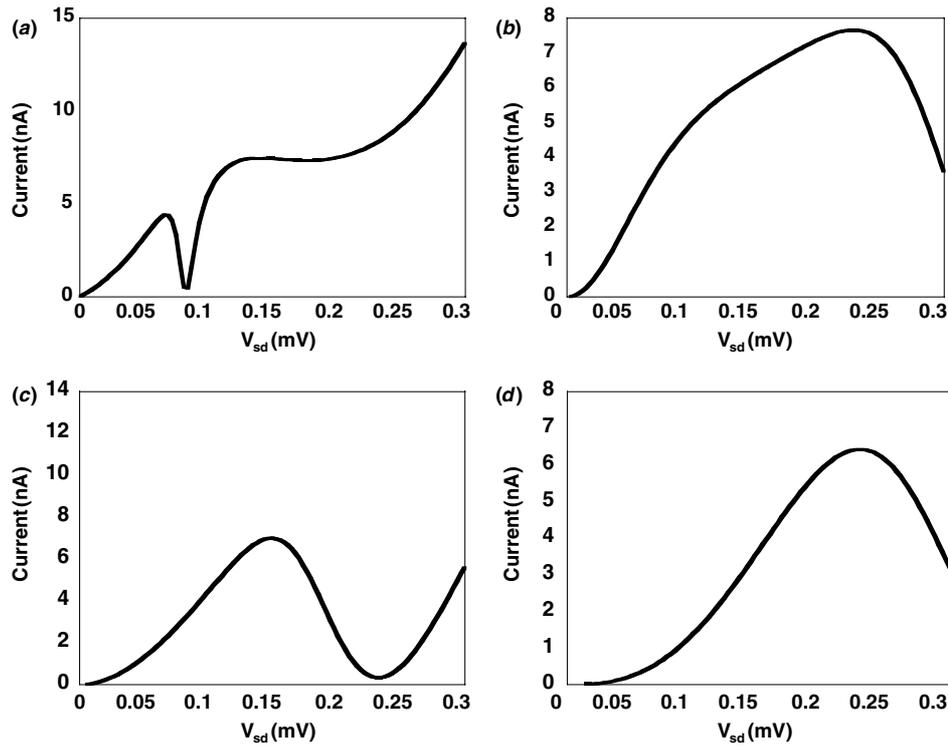
Figure 1. (*a*) *I*–*V* characteristics of the GaAs RCD at 0 K. (*b*) *I*–*V* characteristics of the GaAs RCD at 1 K. (*c*) *I*–*V* characteristics of the GaAs RCD at 2 K. (*d*) *I*–*V* characteristics of the GaAs RCD at 4.2 K.

formula is applied to the transmissions to obtain the current, we have the difference between the Fermi function at the source and the Fermi function at the drain added into the convolution. This causes a lowering of the current from the ideal case. Further, we note that the position of the null has shifted from the ideal case. This can be explained by the fact that as we impart extra energy to the system and more states contribute, it will require more bias to sweep the mode through the next highly reflective state that is responsible for the formation of the null. In figure 1(*c*), we plot the *I*–*V* characteristics with the temperature set to 2 K. In this case enough additional energy has been imparted into the system that the applied bias will then sweep the energy of the mode through the highly reflective state and we once again see the characteristic null. In figure 1(*d*), we increase the temperature of the system to 4.2 K and see similar characteristics to figure 1(*b*). There is not enough energy in the applied bias to sweep the energy of the incoming mode through the next reflective state; therefore, with the bias applied, we are only able to see that the current begins to decrease as the energy of the mode begins to coincide with that of the reflective state. Based on these results, we find that finite temperature does not wash away the presence of the null. It simply shifts its location and forces one to, in some cases, use a higher applied bias to pass the reflective states.

We have demonstrated that the reflective coupling diode (RCD) is a very stable device. We have shown that the device may also operate at temperatures up to 4.2 K without any significant degradation. Nevertheless, the inclusion of finite temperature does offer important insight into the operational parameters of the device as the null present in the *I*–*V* curves shifts with increasing temperature.

Acknowledgment

References

[1] Seabaugh A *et al* 1997 Resonant tunnelling circuit technology: has it arrived? *GaAs IC Symp.* pp 199–222
[2] Helm M Jr *et al* 1989 *Phys. Rev. Lett.* **63** 74
[3] Mendez E *et al* 1991 *Phys. Rev.* B **43** 5196
[4] Morifugi M and Hamaguchi C 1995 *Phys. Rev.* B **52** 14131
[5] Grahn H T *et al* 1990 *Phys. Rev. Lett.* **64** 3163
[6] Pereyra P 1998 *Phys. Rev. Lett.* **80** 2677
[7] Gilbert M J, Akis R and Ferry D K 2003 *J. App. Phys.* **93** 6402
[8] Usuki T, Saito M, Takatsu M, Kiehl R A and Yokoyama N 1995 *Phys. Rev.* B **52** 8244