Franz–Keldysh effect in an optical waveguide containing a resonant tunneling diode

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Optical modulation in a waveguide containing a resonant tunneling diode has been observed. The observations are in agreement with a model which assumes that the modulation effect is due to a Franz–Keldysh band-edge shift produced by the electric field developed over a depletion region association with operation of the resonant tunneling diode. The effect has device potential for optical modulation at microwave frequencies.

Since the discovery1 that the resonant tunneling diode (RTD) has sufficient negative differential resistance (NDR) for practical devices most work has concentrated on entirely electronic devices for microwave generation. Optoelectronic applications of RTDs have been explored in a few articles.2–4 We report on work concerned with the optoelectronic properties of a GaAs optical waveguide containing a resonant tunneling diode. This is a simple, first stage, integration of an RTD with an optical device. The key advantage of introducing an RTD is that it radically alters the electrical characteristics of the waveguide. It introduces negative differential resistance which can give gain and oscillation at microwave frequencies. As far as we are aware this is the first report of an RTD directly incorporated in an optical waveguide and the observation of optical modulation via a Franz–Keldysh shift of the band edge.

The wafer was grown by molecular beam epitaxy (MBE). The RTD consisted of two 1.4-nm AlAs barriers separated by a 7.0-nm GaAs well and was grown in the center of a 1-μm-deep GaAs waveguide with 33% AlGaAs cladding layers. The donor concentration (Si) was 2×1016 cm−3 in the GaAs waveguide region and 2×1018 cm−3 in the AlGaAs cladding and ohmic contact layers.5 The doping in these cladding layers had to be kept as high as possible to minimize series resistance \( R_s \). However, this introduces relatively high losses in the cladding through free-carrier absorption; we estimate for the figures given in Ref. 6 that the free-carrier absorption in the cladding layer is approximately 145.5 cm−1. This is the main compromise in the device; the absorption in the waveguide should be minimized but the series resistance and capacitance have also to be minimized for high-speed operation. The AlAs barriers and GaAs quantum well which form the RTD were undoped.

Figure 1 shows a cross-section schematic of the device. The rib waveguides, 2 to 8 μm wide, are fabricated by dry etching in SiCl4. An ohmic contact recipe, Au:Ge:Au:Ni:Au, was used as the dry etch mask. After dry etching the ohmic contact was etched into shorter lengths, 100 to 400 μm, before being annealed to form the emitter contact of the diode. The collector contact was deposited on both the back face of the substrate and on either side of the rib. The Au etch also removed the top \( n^+ \) GaAs contact layer, this helped to confine the current from spreading much beyond the length of the contact and defined the active region of the waveguide. A SiO2 layer was deposited by chemical vapor deposition and a window was etched above the waveguide electrode allowing contact from a bonding pad.

The dc characteristics give a measure of the negative resistance region of the current-voltage (I–V) curve. Several types of devices have been characterized. All have been based on the cross section shown in Fig. 1. The device that was employed for our Franz–Keldysh band-shift measurements consisted of a 4-μm-wide optical waveguide with a 200-μm-long contact defining an active area of 800 μm². Figure 2 shows the I–V curve for this optical waveguide RTD. Resonance was found to occur at a bias of 0.9 V with a sharp drop in the current indicating bistability but not oscillation.

It is interesting to note that we have also made smaller (<400-μm²) optical waveguide RTDs from the same wafer as the larger device which, when measured on a Witron network analyzer, show oscillations at frequencies up to 56 GHz although the maximum frequency for these devices was calculated from Eq. (1) in Ref. 7 to be 45 GHz. These smaller devices show the characteristic plateau-like structure in the I–V curve associated with oscillations. In principle the larger device should also oscillate as no change in the nature of the instability in the NDR region should be expected with an increase in diode area. The reason for not observing oscillation in the larger devices is currently being investigated.

The optical characterization was carried out on the larger device which exhibited the electrically bistable characteristic.
with the aim of determining the change in the optical absorption spectrum when the device switched. Optical characterization of the device employed a Ti:sapphire laser which was tunable in the wavelength region close to the band-gap resonance of the waveguide, i.e., close to 890 nm. Approximately 1 mW of light from the laser was coupled into the waveguide by an end-fire arrangement. The RTD was biased electrical pulses of around 10-μs duration and period of 100 μs. The pulses were employed to minimize thermal effects. Typically, when the pulse amplitude exceeded the peak voltage of the RTD, \( V_b \), the current drawn from the pulsed power supply would fall rapidly, the voltage across the device would then fall below \( V_b \), and the current would increase till the voltage exceeded \( V_b \) causing the device to switch again. A high-speed detector was used to measure any change in the intensity of the transmitted light when the device was biased just above \( V_b \). The time scale of the NDR induced pulse ~2 μs minimizes the possibility of thermal effects inducing any electroabsorption.

A decrease in the intensity of the transmitted light was observed upon switching due to the RTD. Below the resonance condition in the RTD, \( V<\approx V_b \), the current tunnels through the barriers with only a small accumulation and depletion region formed on either side of the barriers. Above the resonance condition, \( V>\approx V_b \), the carriers can no longer tunnel through the barriers and a large depletion region is formed over which an electric field is dropped. This gives rise to a decrease in current that is observed as a switch between \( b \) and \( c \) in the \( I-V \) curve shown in Fig. 2. It is this field dropped across the depletion region that is responsible for the increase in absorption through the Franz-Keldysh effect. The results are shown in Fig. 3, where the change in the transmission coefficient associated with the bistable switching of the device is plotted against wavelength. The absorption of undoped bulk GaAs, taken from the literature (Ref. 6), is also shown in Fig. 3. There is a shift in the band edge of approximately 14 nm. For a 300-μm-long device, a maximum modulation depth of 7 dB at approximately 910 nm was observed.

The simple model we propose for the observed effects described above is that a built in field is dropped across a depletion region which is formed when the sample is biased above its resonance condition. When the bound state of the GaAs quantum well is aligned to the conduction band the transmission coefficient is close to unity and the electrons can easily tunnel through the barriers with little depletion of the carriers at the barriers. Once the bound state is pulled below the conduction band the electrons can no longer tunnel through the barriers and a depletion and accumulation region will be formed on either side of the barriers. In Fig. 2 the current at point \( b \), \( I_b \), is given by \( V_b/R_s \), where \( R_s \) is the total series resistance of the device including contact resistance and material resistivity. At point \( c \) the current has dropped sharply to \( I_c \) with no change in either the series resistance or the external biasing voltage. The difference in current can be accounted for by the internal voltage dropped across the depletion region, \( V_d \).

From the above analysis we have

\[
I_b R_s = V_b = V_c = I_c R_s + V_d
\]

or

\[
V_d = V_b \left( \frac{1 - I_c}{I_b} \right)
\]

The field dropped across the depletion region gives rise to a Franz-Keldysh shift of the band edge (i.e., a shift in the absorption edge of the waveguide to longer wavelength). The magnitude of the field, \( E \), is given approximately by (we assume a uniform field)

\[
E = \frac{V_d}{D}
\]

Although the field dropped across the RTD will be very large, the overlap of this region with the optical mode will be very small, less than 0.01, and has been ignored in our calculations of the Franz-Keldysh effect. The width of the depletion region created by the double barriers of the RTD is given by Ref. 7

\[
D = \left( \frac{W^2 + \gamma - \frac{\epsilon}{c N_d} - V_d}{\epsilon N_d} \right)^{1/2}
\]

where \( W \) is the width of the double barrier structure and \( N_d \) is the doping level, \( \epsilon = \epsilon_c \epsilon_0 \) is the dielectric constant. We take \( \epsilon_c = 13 \).

For a measured biasing voltage of 0.9 V and a peak to valley ratio, \( I_b/I_c \), of 1.6, the calculated value of \( V_d \) is 0.34 V.
and the width of the depletion region is calculated to be 0.157 μm. This gives a field of 2.20 MV m⁻¹ across the center of the waveguide. The applied electric field changes the band gap by an amount given by Ref. 8

\[ S = - \left( \frac{eEh}{2m^*} \right)^{1/3} \]

where \( m^* \) is the effective reduced mass given by \( (m_e^{-1} + m_h^{-1})^{-1} \). This corresponds to a shift in the absorption edge towards longer wavelengths of 9 nm. The agreement with the observed shift of 14 nm is reasonable considering some of the approximations such as regarding the electric field across the depletion region as uniform.

An RTD has been incorporated directly into an optical waveguide and electroabsorption has been observed in a bistable device. The results are consistent with a Franz–Keldysh shift in the band edge produced by an electric field which is generated by the voltage drop across the depletion layer. The depletion layer is associated with the tunneling process through the diode.

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