Optical modulation at around 1550 nm in an InGaAlAs optical waveguide containing an InGaAs/AlAs resonant tunneling diode

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We report electroabsorption modulation of light at around 1550 nm in a unipolar InGaAlAs optical waveguide containing an InGaAs/AlAs double-barrier resonant tunneling diode (RTD). The RTD peak-to-valley transition increases the electric field across the waveguide, which shifts the core material absorption band edge to longer wavelengths via the Franz–Keldysh effect, thus changing the light-guiding characteristics of the waveguide. Low-frequency characterization of a device shows modulation up to 28 dB at 1565 nm. When dc biased close to the negative differential conductance region, the RTD optical waveguide behaves as an electroabsorption modulator integrated with a wide bandwidth electrical amplifier, offering a potential advantage over conventional *pn* modulators. [S0003-6951(99)00748-2]

Because of their intrinsic high-speed response and potential for electrical gain over a wide bandwidth, resonant tunneling diodes (RTDs) have been proposed by several groups[1–3] for optoelectronic applications. Previously, we reported work on an GaAs/AlAs RTD that was successfully integrated in a unipolar GaAs–AlGaAs optical waveguide,[4] and high-speed optical modulation (up to 18 dB) combined with electrical gain was demonstrated.[5] This device operated around 900 nm. For devices functioning at the usual optical communication wavelengths, 1300 or 1550 nm, applications could include, for example, optical distribution of modulated millimeter-wave frequency carriers for mobile communication systems. In this letter we describe a resonant tunneling diode electroabsorption modulator (RTD-EAM) operating at wavelengths around 1550 nm.

The operation of the device is based on a RTD within an optical waveguide which introduces a nonuniform electric field distribution across the waveguide core. The electric field becomes strongly dependent on the bias voltage, due to accumulation and depletion of electrons in the emitter and collector sides of the RTD, respectively. Depending on the dc bias operating point, a small high frequency ac signal (<1 V) can induce high-speed switching. This produces substantial high-speed modulation of the waveguide optical absorption coefficient at a given wavelength near the material band edge via the Franz–Keldysh effect[4] and, therefore, modulates light at photon energies lower than the waveguide core band-gap energy. The modulation depth can be considerable because, under certain conditions, the RTD operation point switches well into the two positive differential resistance portions of the current–voltage (I–V) characteristic, with a substantial part of the terminal voltage dropped across the depleted region in the collector side.[5,6] The advantage of the RTD-EAM compared to conventional *pn* modulators is that, when dc biased close to the negative differential conductance (NDC) region, the device behaves as an optical waveguide electroabsorption modulator integrated with a wide bandwidth electrical amplifier.

The high-frequency and large modulation depth characteristics of the RTD-EAM are a direct consequence of the carrier transport mechanisms across the RTD and the waveguide depletion region. They are closely related to the material system and the specific device structure. High-speed performance can be improved by increasing the differential negative conductance, G_n, or decreasing the series resistance, R_s. The velocity of the carriers, ν, and hence the carriers transit time across the whole structure, are material and structure dependent. To obtain a larger value of G_n, it is necessary to achieve a high peak current density, J_p, and high peak-to-valley current ratio (PVCR), J_p/J_ν.

The demonstration and development of this new modulator concept in the InGaAs–InAlAs material system lattice matched to InP is a promising route towards high speed, low radio frequency (rf) power consumption, optoelectronic converters (rf optical and optical rf), because it can cover the wavelength range of 1.0–1.6 μm where optical fibers have the lowest loss and chromatic dispersion. For wavelengths around 1550 nm, we employ a unipolar $In_{0.53}Ga_{0.42}Al_{0.05}As$ optical waveguide containing an InGaAs/AlAs double-barrier resonant tunneling diode (RTD). Furthermore, due to a smaller effective mass of the electrons in InGaAs (0.045 m_0 compared to 0.067 m_0 for GaAs), and a larger Γ_{InGaAs}-X_{AlAs} barrier height (0.65 eV compared to 0.20 eV for GaAs/AlAs) which will reduce the parasitic Γ-X medi-

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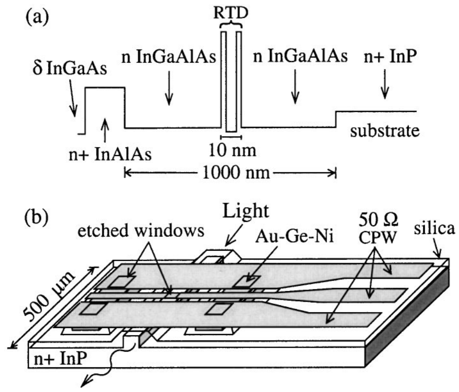

FIG. 1. (a) Schematic diagram of the wafer structure. (b) The RTD optical modulator configuration.

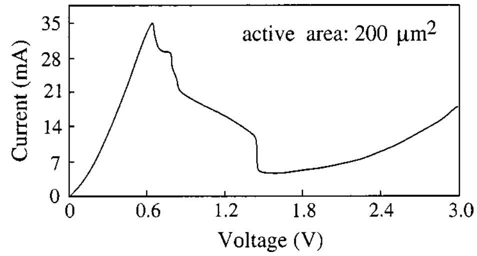

FIG. 2. Experimental I–V characteristic of a 2 μm×100 μm active area RTD optical waveguide, showing a PVCR around 7 and a peak current density of 18 kA/cm^2.

ated transport, the InGaAs–InAlAs material system has improved tunneling characteristics with a superior peak-to-valley current ratio, evident in the dc current–voltage characteristic. In addition, a specific contact resistivity below 10^{-7} Ω cm^2 and a saturation velocity above 10^7 cm/s can be achieved changing the material to InGaAs–InAlAs,[7,8] (for GaAs/AlGaAs, typical metal to n^+-GaAs contacts have a specific contact resistivity of about 10^{-6} Ω cm^2, and the saturation velocity of electrons in GaAs layers is less than 10^7 cm/s). Because InGaAs/AlAs RTDs can present higher peak current density and smaller valley current density, higher-speed operation can be expected. In summary, compared to the GaAs/AlAs system, the use of an InGaAs/AlAs RTD in an InGaAlAs optical waveguide not only permits operation at optical communication wavelengths but also leads to a significant improvement in the electrical characteristics of the device.

The InGaAlAs RTD optical waveguide structure was grown by molecular beam epitaxy in a Varian Gen II system, on a n^+ InP substrate [Fig. 1(a)]. It consists of two 2-nm-thick AlAs barriers separated by a 6-nm-wide InGaAs quantum well, sandwiched between two 500-nm-thick moderately doped (Si:5×10^{16} cm^{-3}) $In_{0.53}Ga_{0.42}Al_{0.05}As$ spacer layers which form the waveguide core. The InP substrate and the top heavily doped (Si:2×10^{18} cm^{-3}) InAlAs region provide the waveguide cladding layers, which confine the light in the direction parallel to the double barrier plane. A δ-doped InGaAs cap layer was provided for formation of Au–Ge–Ni ohmic contacts. With suitable design, good overlap can be achieved between the electric field and the modal distribution of the waveguide; the longitudinal character of the interaction allows large light modulation to be achieved.

Ridge waveguides (2–6 μm wide) and large-area mesas on each side of the ridges were fabricated by wet etching. Ohmic contacts (100–400 μm long) were deposited on top of the ridges and mesas. The waveguide width and the ohmic contact length define the device active area. A SiO_2 layer was deposited, and access contact windows were etched on the ridge and the mesa electrodes [Fig. 1(b)], allowing contact to be made to high-frequency bonding pads [coplanar waveguide transmission line (CPW)]. After cleaving, the devices were die bonded on packages allowing light to be coupled into the waveguide by a microscope objective end-fire arrangement.

The dc I–V characteristics of packaged devices were measured using a HP 4145 parametric analyzer and show typical RTD behavior. From the I–V characteristic we can estimate the electric field change across the depleted portion of the waveguide core due to RTD peak-to-valley switching. Figure 2 shows the I–V characteristic of a 2 μm×100 μm active area RTD. Typical devices have peak current density around 18 kA/cm^2, with a peak-to-valley current ratio (PVCR) of 4. The difference between the valley and peak voltages, ΔV, is around 0.8 V, and the difference between the peak and valley current densities, $\Delta J = J_p\ (1-\mathrm{PVCR}^{-1})$, is about 13.5 kA/cm^2. (Our typical GaAs/AlAs devices show a PVCR around 1.5, $J_p \simeq 13$ kA/cm^2, $\Delta V \simeq 0.4$ V, and $\Delta J \simeq 5$ kA/cm^2.)

Two important figures of merit of the modulator can be estimated from the RTD dc characteristics, and for a given material system they can be tailored by structural design. They are the modulator bandwidth, which is related to the 10%–90% switching time, t_R, of the RTD between the peak and valley points, and the modulation depth, which is related to the peak-to-valley current ratio. The RTD switching time can be estimated from $t_R = 4.4\ (\Delta V/\Delta J) C_\nu$,[6] where C_ν is the capacitance at the valley point per unit area ($C_\nu = \epsilon/W$, where ϵ is the dielectric constant, and W is the depletion region width). For the present devices, with $W = 0.5$ μm and $\epsilon = 13\epsilon_0$, $t_R \simeq 6$ ps. From this switching time, we can expect devices with a bandwidth larger than 60 GHz.

Optical characterization of the modulator employed light from a Tunics diode laser, tunable in the wavelength region around the absorption edge of the $In_{0.53}Ga_{0.42}Al_{0.05}As$ waveguide (1480–1580 nm). The laser light was coupled into the waveguide by a microscope objective end-fire arrangement. To measure the change in the optical absorption spectrum induced by the peak-to-valley transition, a low frequency rf signal was injected to switch the RTD between the extremes of the NDC region, and a photodetector was used to measure the transmitted light. The electric field enhancement close to the collector barrier due to the peak-to-valley transition, $\Delta\mathcal{E} \equiv \mathcal{E}_\nu - \mathcal{E}_p$, with $\mathcal{E}_{p(\nu)}$ representing the electric field magnitude at the peak (valley) point, can be estimated using[9]

$$\Delta\mathcal{E} \cong \frac{\Delta V}{W} + \frac{W}{2\epsilon\nu_{\mathrm{sat}}}\Delta J \qquad (1)$$

with ν_{sat} being the electron saturation velocity in the depletion region. Taking $\epsilon = 13\epsilon_0$ and $\nu_{\mathrm{sat}} = 1\times10^7$ cm/s, and assuming the depletion region to be 500 nm wide, we have $\Delta\mathcal{E} \simeq 45$ kV/cm (for the GaAs based device we obtained $\Delta\mathcal{E} \simeq 19$ kV/cm).

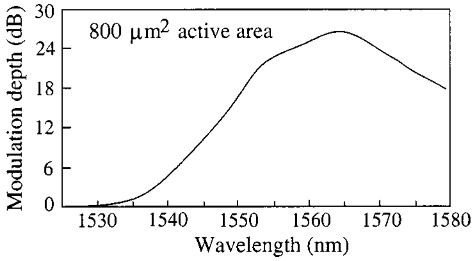

FIG. 3. Modulation depth enhancement as a function of wavelength, induced by the RTD peak-to-valley transition.

Assuming $\mathcal{E}_\nu \gg \mathcal{E}_p$, $\Delta\mathcal{E} \cong \mathcal{E}_\nu$, the shift in the InGaAlAs waveguide transmission spectrum due to electric field enhancement, $\mathcal{E}_\nu$, as a result of the Franz–Keldysh effect, is given approximately by[4]

$$\Delta\lambda_g \cong \frac{\lambda_g^2}{hc}\left(\frac{e^2h^2}{8\pi^2 m_r}\right)^{1/3}\mathcal{E}_\nu^{2/3}, \qquad (2)$$

where m_r is the electron-hole system reduced effective mass, h is the Planck's constant, c is the light velocity, e is the electron charge, and λ_g is the wavelength corresponding to the waveguide transmission edge at zero bias, which is around 1520 nm. Equation (2) neglects any shift due to thermal effects as a consequence of the current flow and effects due to the applied peak voltage. The observed transmission spectrum shift associated with the electric field change is approximately $\lambda_g \simeq 43$ nm, which agrees reasonably well with the 50 nm value obtained using Eq. (2), where a uniform electric field approximation is assumed. [For the GaAs based device we obtained $\lambda_g \simeq 9$ nm from Eq. (2), and we have observed a spectrum shift around 12 nm]. This agreement suggests that Eq. (1) can be used, as a first approximation, to determine the magnitude of the electric field enhancement due to peak-to-valley transition.

Figure 3 shows the modulation depth as a function of the wavelength for peak-to-valley switching induced by a low-frequency (1 MHz) square wave signal with 1 V amplitude, for a 4 μm$\times$200 μm active area device biased slightly below the peak voltage. A maximum modulation depth of 28 dB was obtained at 1565 nm, which is approximately 10 dB higher than the maximum obtained with a GaAs/AlAs device.[5]

In conclusion, optical modulation up to 28 dB has been demonstrated in InGaAlAs optical waveguides containing an InGaAs/AlAs double-barrier resonant tunneling diode (RTD), due to peak-to-valley switching. Integration of a RTD with an optical waveguide, which combines a wide bandwidth electrical amplifier with an electroabsorption modulator, opens up the possibility for a variety of operation modes (such as modulation due to self-oscillation and relaxation oscillation). Previous results obtained with the GaAs/AlGaAs system at 900 nm were confirmed and improved, using the InGaAlAs quaternary compound which allows operation at useful wavelengths in the third fiber optic communication window (around 1550 nm). The device appears to offer a promising route towards a high speed, low power optoelectronic converter (rf optical and optical rf). The high-speed optoelectronic characterization of this new modulator is under way, together with a study of its application as high-speed photodetector.

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[1] A. F. Lann, E. Grumann, A. Gabai, J. E. Golub, and P. England, Appl. Phys. Lett. **62**, 13 (1993).

[2] S. C. Kan, P. J. Harshman, K. Y. Lau, Y. Wang, and W. I. Wang, IEEE Photonics Technol. Lett. **8**, 641 (1996).

[3] T. S. Moise, Y.-C. Kao, C. L. Goldsmith, C. L. Schow, and J. C. Campbell, IEEE Photonics Technol. Lett. **9**, 803 (1997).

[4] S. G. McMeekin, M. R. S. Taylor, B. Vögele, C. R. Stanley, and C. N. Ironside, Appl. Phys. Lett. **65**, 1076 (1994).

[5] J. M. L. Figueiredo, C. R. Stanley, A. R. Boyd, C. N. Ironside, S. G. McMeekin, and A. M. P. Leite, Appl. Phys. Lett. **74**, 1197 (1999).

[6] E. R. Brown, C. D. Parker, S. Verghese, M. W. Geis, and J. F. Harvey, Appl. Phys. Lett. **70**, 2787 (1997); S. Verghese, C. D. Parker, and E. R. Brown, Appl. Phys. Lett. **72**, 2550 (1998).

[7] T. Nittono, H. Ito, O. Nakajima, and T. Ishibashi, Jpn. J. Appl. Phys., Part 1 **27**, 1718 (1988).

[8] A. V. Dyadchenko and E. D. Prokhorov, Radio Eng. Electron. Phys. **21**, 151 (1976).

[9] J. M. L. Figueiredo, C. N. Ironside, A. M. P. Leite, and C. R. Stanley, 5th IEEE International Workshop on High Performance Electron Devices for Microwave and Optoelectronic Applications (EDMO) (unpublished), p. 352 (1997).