WAVEGUIDE AND SURFACE PLASMON COUPLED INFRARED DEVICES USING SEMICONDUCTOR QUANTUM WELLS

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Abstract

In this paper we propose and present detailed calculations on a new method for using the intersubband transition in modulation doped semiconductor quantum wells grown from $Al_xGa_{1-x}As$ and GaAs in infra red devices (modulators and detectors) working at 10 um wavelength. The quantum wells are embedded near the the surface of a thick AlAs layer (1-9 microns) and capped by a metal electrode and coupling to the intersubband transition is mediated by either a "leaky" guided mode or a surface plasmon. Our calculations show that coupling of radiation to intersubband transitions can be strong under such circumstances.

The fabrication of optoelectronic devices such as detectors or modulators operating at 10 μm using the intersubband intransition in a III-V semiconductor system such as $GaAs/Al_xGa_{1-x}As$ would take advantage of the highly developed technologies of these materials and potentially allow the integration of such devices with high speed electronics and optoelectronic devices operating at other wavelengths. The subband energy spacing can be tuned to the energy of 10 μm wavelength photons by choosing a suitable well width, typically 82 A. Dipole selection rules only allow the transition for an electric field oscillating perpendicular to the quantum well. Typical III-V semiconductors tend to have large refractive indices. These will refract incident light so that it propagates with only a small component of its electric field oscillating in the plane of the the well. The light then only couples weakly to the intersubband transition. The spectroscopic studies of the intersubband transition in the literature (1-3) have used light incident at the Brewster angle in order to maximise the component of the electric field oscillating perpendicular to the quantum well. Typically, a peak absorption of 3-5% is obtained from a stack of 50 quantum wells. The weakness of this coupling means that some additional method must be found to increase the strength of interaction with the intersubband transition in order to make a useful optoelectronic device. Lyon and Goosen (4) have considered the use of the resonant modes of a diffraction grating to provide this enhancement. In this paper we propose and present detailed theoretical modelling of, an alternative structure for enhancing the intersubband absorption so that a large proportion of the incident light is absorbed in a small number of quantum wells, typically 4. The carrier density in the quantum wells can now be controlled by a Schottky gate and the absorption modulated. The initial application we propose for this structure is as a reflective modulator.

The structure (see figure 1) consists of a thick, 1-9 microns, layer of AlAs grown on a semi-insulating GaAs substrate. The quantum wells (modulation doped) are grown on top of the AlAs layer and the whole structure is capped with a metal top layer. A GaAs prism with anti-reflection coated surfaces is mounted on the substrate and is used to couple The structure has two different operational modes according to the angle of incidence. When light is incident at an angle slightly less than the critical angle for total internal reflection at the AlAs/GaAs interface a guided wave is launched into the AlAs with its electric field oscillating almost perpendicular to the quantum wells. The second mode of operation involves the excitation of a surface plasmon at the interface between the metal and the semiconductor. The electric field associated with the surface plasmon has a large component perpendicular to the plane of the interface and thus couples strongly to the intersubband transition.

In our calculations each layer is treated as a slab of dielectric and a matrix method which matches the components of E and H in the interfacial planes is used to determine the transmission or reflection coefficients of the structure. This method is similar is similar to that described in reference (5) but the individual layers are allowed to anisotropic. Following Chen et al (6) the quantum wells are ascribed anisotropic dielectric functions given by

$$\epsilon_z = \epsilon_\infty + \frac{f\omega_p^2}{\omega^2 - \omega_0^2 + i\omega\gamma}$$

and

$$\epsilon_x = \epsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i/\tau)}$$

where ω_p is the plasma frequency, defined by the relation $\omega_p = \surd(N_{2d}e^2/\epsilon_0 m^* a)$,a is the well width, N_{2d} is the sheet carrier density, ω is the angular frequency, ω_0 is the intersubband transition angular frequency, f is the intersubband transition oscillator strength, γ is the intersubband linewidth, τ is the relaxation time for in plane transport, z is the direction perpendicular to the quantum well and x and y are directions in the plane of the quantum well. The oscillator strength is defined by the relation $f=(4\pi m^*\omega_0/h)|<1|z|2>|^2$ where $<1|z|2>$ is the transition matrix element. Typical values for f and γ, taken from reference (1) are f=0.9 and $\gamma=8*10^{12}$ s. τ is taken to be 10^{-13} s but has relatively little effect on the calculations. The undoped semiconductor layers are treated as slabs of an isotropic dielectric, with $\epsilon_{AlAs}=8.16$ and $\epsilon_{GaAs}=10.9$. The metal is taken to be an isotropic dielectric with a dielectric constant of the same form as ϵ_x but with $\omega_p=1.36\text{x}10^{16}$ s^{-1} and $\tau=2\text{x}10^{-14}$ s (6).

The operation of the proposed device is shown in figure 2 as curves of reflectivty versus angle, both with and without carriers in the quantum well. (The number of wells is sufficiently small that the wells can be depleted of free carriers by an electric field below the breakdown field of the material.) The operating wavelength is tuned to the peak of the quantum well absorption. This is somewhat higher than the bare intersubband frequency because of an electromagnetic interaction with the carriers in the well (8) and is automatically handled is the anisotropic tensor intoduced above. When the angle of incidence is 59.9°, which is slightly greater than the critical angle for total internal reflection at the GaAs/AlAs interface, and there are no carriers in the quantum well a surface plasmon is launched along the metal semiconductor interface and the reflection coefficient becomes very small. All of the incident power is absorbed in the metal layer. When free carriers are introduced into the quantum well the boundary conditions necessary for the generation of a surface plasmon are destroyed and all of the incident power is reflected. In this mode of operation the quantum wells are used to control the surface plasmon. The width of the surface plasmon reflectivity dip is 0.3.

When the angle of incidence is less than 59°, the angle for total internal reflection, a "guided" propagating wave (rather than an evanescent wave) is launched into the AlAs with a large electric field component perpendicular to the quantum wells. Strong intersubband absorption now occurs and is evidenced by a large decrease in the reflectivity when free carriers are present in the quantum well. The metal overlayer ensures that the electric filed is perpendicular to the quantum wells. Strong absorption occurs at particular angles of incidence (e.g. 57°) where the interference of the forward and backward waves results in a maximum of the perpendicular electric field at the metal semiconductor interface. One and a half periods of standing wave are contained in the AlAs layer at this angle of incidence.

The thick AlAs layer (9 μm) is necessary for the surface plasmon mode of operation whereas the guided wave mode of operation works better with a thinner layer of AlAs when only one half a period of standing wave is contained in the AlAs layer. The calculated reflectivity of a structure with a structure with a 2.1 μm AlAs layer is shown in figure 3. The maximum fraction of the light absorbed is >95% and the angular half width of the reflectivity dip is >10°. In conclusion, we have demonstrated a method of obtaining a strong enhancement of the optical absorption in semiconductor quantum wells by either embedding the wells in a "waveguide" or by coupling the intersubband transition to a surface plasmon and proposed that an infrared modulator would be possible. The waveguide mode could also be used as detector if the absorption "mobilized" electrons possibly in the way demonstrated recently by Levine et al (9).

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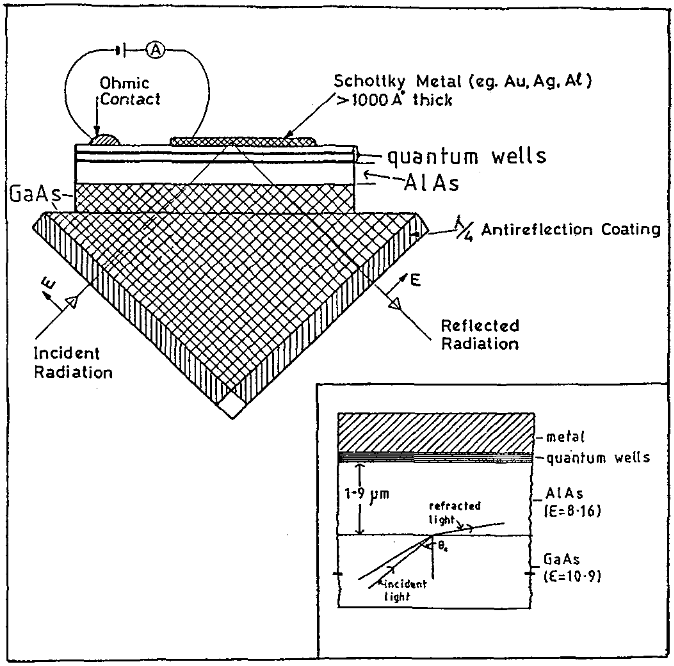

Figure 1 The details of the device structure discussed in this paper, including an expansion of the part containing the quantum wells (the inset).

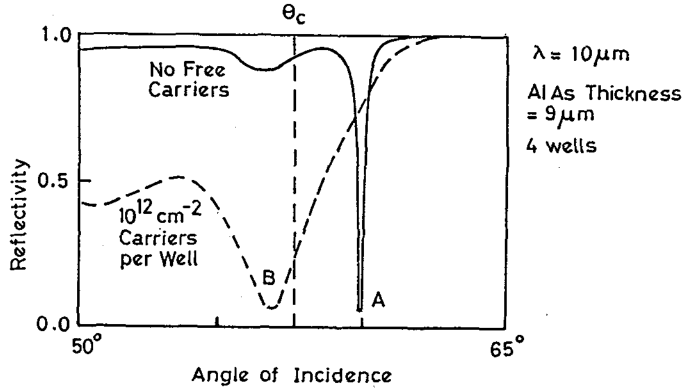

Figure 2 The calculated operation of the device as a modulator shown as plots of reflectivity versus angle both ,with and without carriers present. The operating frequency corresponds to 10 μm wavelength in free space and the intersubband absorption is tuned to this frequency. This device has a thick 9μm AlAs layer and contains four quantum wells.

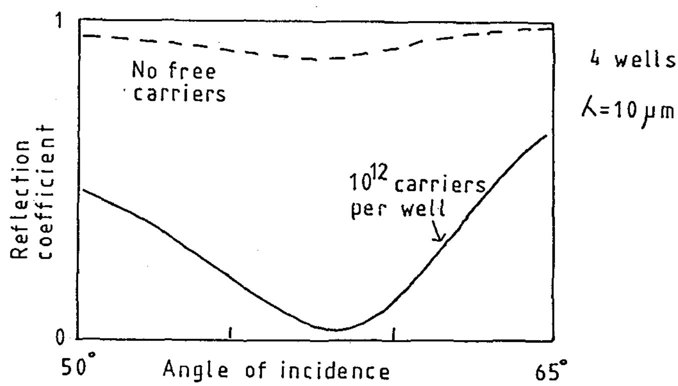

Figure 3 The calculated operation of a device with a thin (2.1 μm) AlAs layer and four quantum wells. The waveguide mode is stronger and broader than in figure 2.