A new infrared detector using electron emission from multiple quantum wells

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A new type of infrared photodetector using free electron absorption in a heavily doped GaAs/GaAlAs quantum well structure has been demonstrated. Preliminary results indicate a strong response in the near infrared with a responsivity conservatively estimated at 200 A/W. The structure can potentially be tailored during fabrication for use in several infrared bands of interest, including the 3 to 5 micron band and the 8 to 10 micron band.

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The advent of molecular beam epitaxy makes possible the fabrication of devices with complicated band structures and a high degree of control over important parameters such as doping profiles, band discontinuities, and layer thicknesses.[1] High quality large-area wafers may be grown with layer thickness control of a few angstroms. A new type of infrared photodetector has been demonstrated which allows this high degree of control to enable the tailoring of such characteristics as its cutoff wavelength and the tradeoff between its photoconductive gain and response time.

The body of the device consists of a heavily doped multiple quantum well structure formed by alternating layers of semiconductors which form heterojunctions with a conduction-band discontinuity of the desired magnitiude, in this case GaAs and GaAlAs. A typical band diagram is shown in Fig. 1. The device is operated at a temperature sufficiently low that nearly all of the electrons are trapped in the quantum wells. When a bias voltage is applied across the structure, little current flows in the absence of light due to the lack of carriers outside the quantum wells. The structure may be uniformly doped rather than modulation doped because the presence of donors in the quantum well layers is not detrimental to the operation of the device. Free-carrier absorption excites electrons out of the quantum wells allowing current to flow in the external circuit. The device thus acts as a photoconductor, similar in some respects to extrinsic silicon and germanium devices,[2] with the impurity traps of these devices corresponding to the quantum wells of the free electron absorption device.

The cutoff wavelength of this device is determined by the depth of the conduction-band quantum wells. Photons with less energy than that necessary to excite electrons out of the quantum wells will be absorbed, but these absorptions do not contribute to the detection current because the electrons thermalize back into the same quantum well. The dark current of the device is due to the thermal excitation of electrons over the same barriers. If the device is fabricated with a lower barrier height, the cutoff wavelength will be increased, and the dark current at a given temperature will also increase. Direct control of this tradeoff between cutoff wavelength, device sensitivity, and cooling requirements of the device simply by varying the aluminum mole fraction of the barrier regions may make possible the fabrication of particular devices optimized for several bands of interest, including the 3 to 5 micron band and the 8 to 10 micron band.

The mechanism of this device is similar to that of the Schottky-barrier detector,[3] with the metal replaced with a heavily doped semiconductor. The low density of electrons in the semiconductor compared to that in a metal is partially made up for by the large number of active interfaces in this structure, however, the total number of electrons participating in the absorption is still small compared to that in a metal. The free-carrier absorption in the quantum wells was also shown in Ref. 4 to be enhanced over the bulk free-carrier absorption by a factor:

$$\frac{\alpha_{Q2D}}{\alpha_{3D}} \approx \left(\frac{2\pi\hbar^2}{m_c kT}\right)^{1/2} \frac{N}{L},$$

where L is the width of well and N is the number of confined states. Calculated values at 77 K are shown in Fig. 2.

To increase the sensitivity, the device demonstrated used a waveguide geometry, allowing more of the light to be ab-

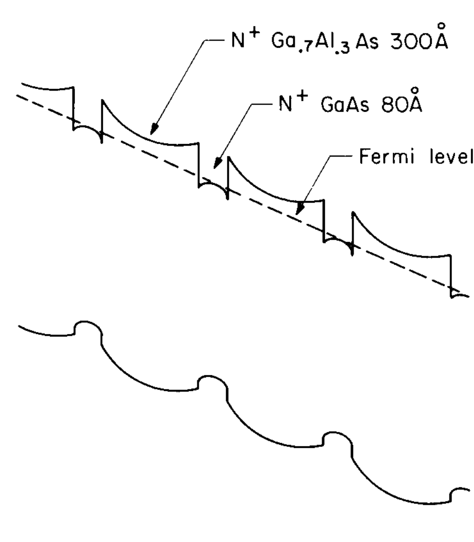

FIG. 1. The band diagram of the device under an applied bias of 2 V.

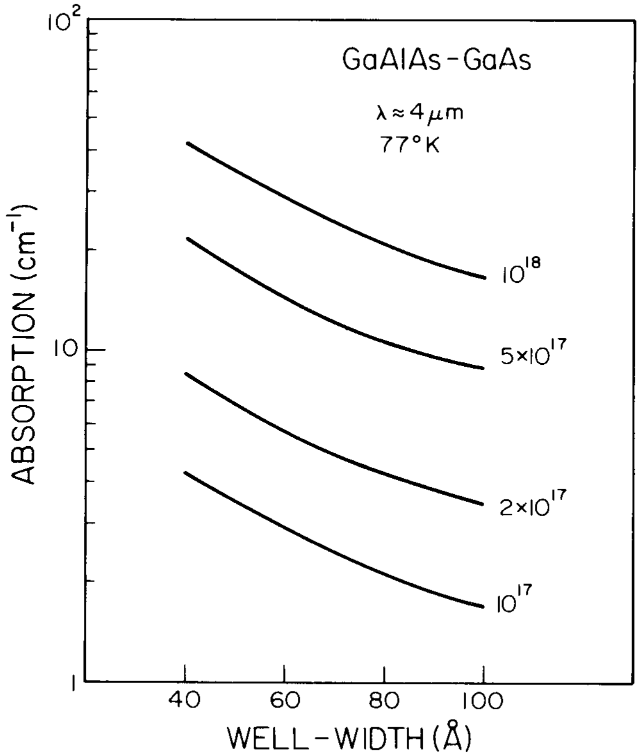

FIG. 2. Calculated coefficient of free electron absorption at 77 K for different electron concentrations.

sorbed due to the increased interaction length. Results which have been obtained since the fabrication of the original device indicate that the absorption of the electrons within the quantum well may be enhanced sufficiently compared to that of three-dimensional free electrons so that the waveguide geometry may not be necessary for good sensitivity.

The device demonstrated consisted of 20 80-Å quantum wells of GaAs and 300-Å barrier layers of $Ga_{1-x}Al_xAs$ ($x = 0.3$). The structure was doped with a uniform flux of Sn, providing a donor density of approximately 3×10^{19} cm^{-3}. The band diagram for the device is shown in Fig. 1. Due to the aluminum effusion cell being operated at a constant current rather than a constant temperature, the aluminum layers were graded slightly. This was anticipated and was expected to enhance electron transport in the direction of the grading.

Upper and lower claddings 1.5 microns thick of $Ga_{1-y}Al_yAs$ ($y = 0.4$) were grown to provide an optical waveguide. The device was grown on a N^+ GaAs wafer, and a 2000-Å N^+ GaAs contact layer was used to provide Ohmic contact at the low operating temperatures.

After the growth was completed, the wafer was removed from the mounting block and the back was lapped to remove the indium solder and allow photolithography. Transverse isolation was provided by etching away the contact layer and part of the upper cladding outside of a 15-micron stripe. Silicon nitride was then deposited by chemical vapor deposition, openings were etched over the previously etched mesas, and AuGe/Au contacts were alloyed to the top and bottom. The wafer was cleaved in bars to provide a geometry similar to that of a stripe contact double heterostructure laser, as shown in Fig. 3, to be used as an edge detector. The completed device had a receiving aperture of 0.5 by 15 microns, and an interaction length of 150 microns.

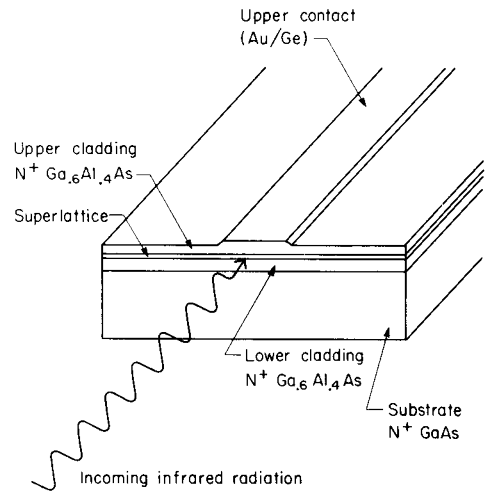

FIG. 3. Schematic diagram of the detector structure.

For preliminary testing, the device was mounted on a copper block and submerged in a bath of liquid nitrogen. The device was illuminated with approximately 10^{-8} W of broadband near-infrared radiation (a 2700 °C source with a GaAs filter was used). The dc current–voltage curve of the device is shown in Fig. 4. The responsivity at 2 V of applied bias was estimated at 200 A/W.

One of the most surprising results of the device testing was the slow response, with the current perceptibly continuing to fall for more than 1 s after the light was removed from the detector. This slow response can be seen as the result of a very low electron capture probability for the quantum well structure at the applied bias, and that the current is limited, given by thermionic emission over the initial barrier. When a

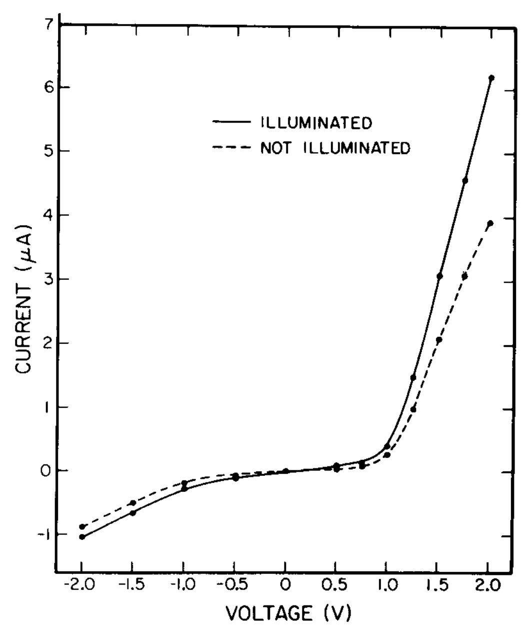

FIG. 4. Current–voltage characteristic at 77 K with illumination of 10^{-8} W of near-infrared radiation.

free-carrier absorption occurs, exciting an electron out of a quantum well, it is accelerated by a field of approximately 10^4 V/cm and has a capture probability for succeeding wells which can be deduced from the photoconductive gain to be approximately one part in 10^4. The structure is then left with a unit positive charge. Since the carrier density is low in the GaAlAs region near the initial barrier, which is the edge of the first quantum well, the field from the excess charge extends into this layer and reduces the effective barrier height. The current rises above its dark level due to the increased thermionic emission over the initial barrier. This continues until an electron is captured, neutralizing the excess charge. Between the initial absorption and the eventual electron capture, an average of approximately 10^4 electrons pass through the structure. Thus the photoconductive gain is large, approximately 10^4, but the device response time is approximately 1 s, this being the average time between a photon absorption and the final electron capture. This effect is similar to that found in extrinsic photoconductive detectors. Another effect of undetermined importance is an avalanche mechanism, where electrons propagating through the structure elastically scatter from electrons trapped within the wells transferring enough energy to allow them to escape the well. Unlike the typical Auger avalanche process, no holes are released, and the noise increase[5] which results if they are not prevented from participating in the avalanche process is completely avoided. If devices in which avalanche is the important gain mechanism prove feasible, they should have response times on the order of the transit time of the device, which is very short.

The probability for capture of a high-energy electron by a quantum well is one of the important parameters of the device, determining the photoconductive gain and the response time. This probability can be adjusted during the growth by varying the width of the quantum wells, with a wider well allowing electrons to thermalize and be captured by the well before making it across.

Potential advantages of this device structure include the increased efficiency of the device over the Schottky-barrier device due to elimination of absorption far from the interface which does not contribute to the detected current, and the built-in electric field on each of the quantum wells due to the separation of the electrons from their parent donors in the barrier region that increases the likelihood that excited carriers will escape the well region, which also increases the efficiency. The small transit time for such a device structure implies that the potential speed is very high, since the energetic carrier lifetime can be made short by increasing the width of the quantum wells.

The high degree of transparency of the structure for electrons allows the fabrication of devices with a thick quantum well structure, which would be needed in the surface detecting geometry due to the long absorption length. This, together with the GaAs/GaAlAs construction which would allow integration with other electronic devices such as amplifiers and multiplexers, is necessary for the construction of large two-dimensional arrays.

The type of device we have proposed and demonstrated has flexibilities not found in other infrared detectors, including tailoring of the cutoff wavelength, which may allow the fabrication of devices which are useful in several bands of interest in the near and mid infrared. Fabrication in GaAs allows the possibility of the construction of large two-dimensional arrays, provided that the surface detection geometry proves to have sufficient sensitivity. The device demonstrated shows a strong response in the near infrared, and although the response rate of the demonstrated device is slow, much higher speeds may be possible.

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