Wavelength-selective voltage-tunable photodetector made from multiple quantum wells

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We show that a *pin*-doped multiple quantum well (MQW) diode can be used as a photodetector whose voltage of maximum photocurrent is wavelength dependent. The voltage of maximum photocurrent can be located accurately and related to the wavelength of the incident light, allowing measurements of the wavelength with a precision of 0.03 Å = 1.2 GHz. This provides a simple, compact, solid-state device that can be simultaneously used to measure the intensity and wavelength of an optical beam. Furthermore, the device shows high responsivity, low dark current, and fast response.

For many applications, it is necessary to measure the intensity and wavelength of an optical beam simultaneously. These applications would include maintaining the mode-suppression ratio of an injection laser[1] and stabilizing the frequency of a single-frequency laser used in a coherent communication system.[2] Previously this has been done with a series of optical elements, such as filters or individual wavelength-selective detectors.[3] In this letter, we show that this task can be accomplished with high precision using a single element: a wavelength-selective, voltage-tunable photodetector made from a *pin*-doped multiple quantum well (MQW) sample.

The novel optoelectronic properties of MQW's have been intensely studied recently. The room-temperature ab-

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sorption spectrum displays an unusually sharp band edge, with a double-peaked structure caused by excitons whose binding energy is enhanced by their two-dimensional confinement. This effect has been seen in GaAs/GaAlAs[4] and GaInAs/AlInAs[5] MQW's. When an electric field is applied to the quantum wells perpendicular to the heterostructure layers, the exciton absorption peaks shift to lower energies.[6] This is due to changes in the particle confinement energies in the wells and a change in the exciton binding energy.[7] The overall shift of the exciton peaks has been described as a quantum-confined Stark effect,[7] and this novel mechanism is, so far, unique to quantum wells. The change in absorption coefficient with voltage at fixed wavelength is much greater in the quantum wells than in bulk semiconductors,[8] so the MQW's can be used to make attractive devices, such as a high-speed modulator,[9] an optically bistable device,[10] an optical switch,[11] and a linearized modulator.[12]

In this letter, we show that the shift of the optical absorption maximum to longer wavelength with applied voltage can be used to make a photodetector whose voltage of maximum photocurrent is wavelength dependent. In this device, we use the fact that the photons thus absorbed will be converted to electron-hole pairs, which are collected in the external contacts as photocurrent. If light of photon energy slightly less than the zero-field absorption maximum illuminates the detector, the photocurrent will be maximized when the applied voltage is just great enough to shift the absorption maximum to align with the incident light. If the photon energy of the light shifts, this "voltage of maximum response" will shift as well. It is this effect which is used in this device to perform wavelength discrimination.

To explore the usefulness of MQW devices as photodetectors, we used molecular beam epitaxy to fabricate a *pin*-doped diode with 50 GaAs quantum wells, each 95 Å wide, in the undoped region. A 95-μm-diam mesa, with a 25-μm-diam optical window, defined the diode, which was similar to those used previously for modulation experiments.[9] In order to characterize its high-speed performance, the diode was mounted in a high-speed package, which contained a microstrip line, a bias tee, and a 50-Ω rf termination, which shunted the diode to ground. For measurements of the diode's wavelength selectivity, the sample was illuminated with the output of one of two commercial single-frequency injection lasers, which could be tuned by varying their temperature.

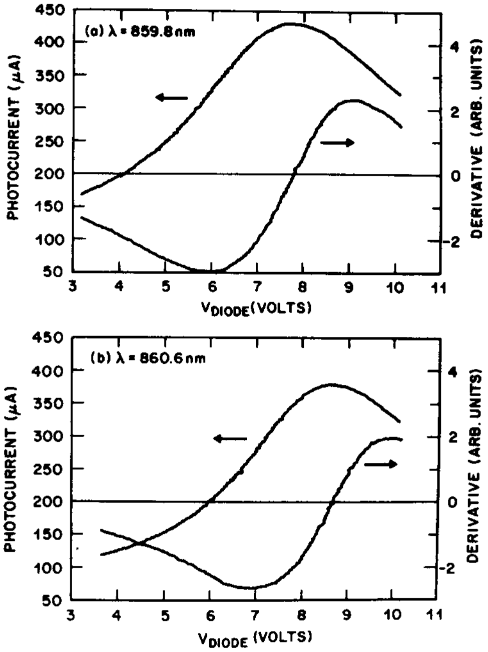

FIG. 1. $I(V)$ and $-(\partial I(V)/\partial V)$ for the detector at two wavelengths. Part (a) taken with optical input at 859.8 nm; part (b) at 860.6 nm.

The wavelength selectivity of the diode can best be determined by evaluating its current-voltage characteristic $I(V)$ and the voltage derivative of this function, $\partial I(V)/\partial V$. To measure these, the output of a slow ramp generator was applied to the dc input of the sample bias tee after passing through a digital ammeter, which recorded $I(V)$. The voltage applied to the bias tee was also recorded, and corrected for the voltage drop in the bias tee. To measure the derivative, a 0.1-V rms 100-Hz ac signal was applied to the rf input port of the bias tee, and the in-phase voltage drop across a 1000-Ω resistor in series with the oscillator was taken as a measure of the differential current flow. Both $I(V)$ and $\partial I(V)/\partial V$ functions were recorded on a digital averaging oscilloscope, which allowed for baseline subtraction of small parasitic signals measured in the absence of light. The total acquisition time for the derivative curves was ~20 s/V.

The upper trace in Fig. 1(a) shows the $I(V)$ curve when the device was illuminated with 150 μW of light at a wavelength of 859.8 nm. The lower trace shows the $-(\partial I(V)/\partial V)$ curve under the same conditions. Figure 1(b) shows these data when the device was illuminated with 860.6-nm light. As described above, each $I(V)$ curve shows a maximum, and the voltage of maximum response shifts from 7.77 to 8.67 V as the wavelength of the light shifts by 0.8 nm. This voltage can be precisely located as the zero-crossing voltage of the derivative curve.

Figure 2 shows the voltage of maximum response plotted as a function of the wavelength of the incident light. A linear regime with a slope of 0.98 V/nm is observed over a 6-nm range. At short wavelengths, the curve flattens because the incident light is approaching the wavelength of maximum absorption for the exciton in zero field. This experiment establishes no long wavelength cutoff for the device, although previous experiments with similar samples have

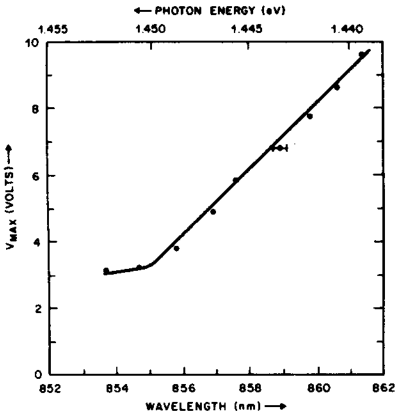

FIG. 2. Voltage of maximum response vs wavelength of optical input for the detector.

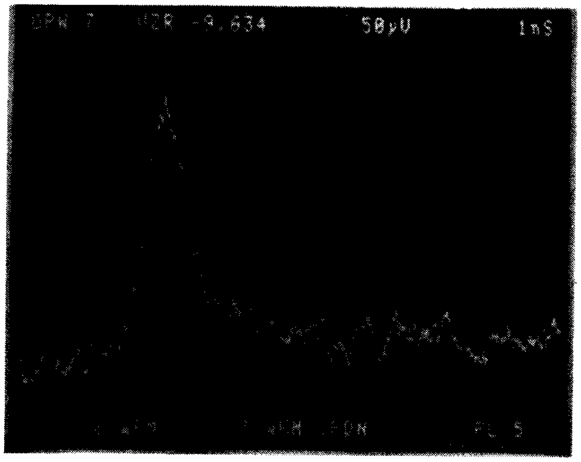

FIG. 3. Time-resolved photoresponse of the detector, when illuminated with 4-ps optical pulses at $\lambda = 861$ nm with a 8-V bias.

shown that the exciton peaks become virtually unresolvable with applied voltages greater than ~20 V,[6] so this will provide an upper limit to the voltage tunability of the device.

This device can be used to determine the wavelength of an incident optical beam with a precision that is limited by the noise in the curves of Fig. 1. For these data, the noise in the derivative curves produces an rms uncertainty of 3 mV in the zero-crossing voltage, which implies that the light wavelength can be estimated with a precision of 0.03 Å = 1.2 GHz, providing long-term drifts, such as temperature fluctuations, can be eliminated. We have confirmed that the shift in energy of the exciton peaks in MQW's is close to that of bulk GaAs, which is 2.6 Å/K.[13] Thus, to reduce temperature fluctuations to the level of other noise sources in this experiment, it will be necessary to regulate the detector temperature to ~ ± 0.01 K. Greater precision in wavelength estimation may be possible with this device, using lower noise circuits, better temperature regulation, more sophisticated peak-locating schemes, or longer averaging times.

We have performed additional tests on the sample to evaluate its potential as a photodetector. We have measured its photocurrent as a function of incident power, and found a linear response between 10 and 250 μW with an external responsivity of 0.40 A/W at a wavelength of 855.7 nm. Experiments on similar samples have shown good linearity down to ~20 nW. This is consistent with an internal quantum efficiency of approximately unity. The dark current at a bias of 16 V was also found to be less than 1 nA.

Finally, we have made initial measurements of the speed of response of this device. The packaged device was illuminated with approximately 4-ps-long pulses from an InP ultrashort-cavity film laser[14] operating at 861 nm. The sample was biased to 8 V and the current pulse generated was detected on a sampling oscilloscope. The observed trace is shown in Fig. 3. A fast component of the response is seen, with a full width half-maximum of 800 ps, along with a small slow component with ~4 ns decay time. The device capacitance would imply a minimum photopulse width of ~200 ps. However, the response is slowed down by the speed with which carriers can be emitted through the 50 MQW's and reach the electrodes.[15] This effect is probably responsible for the observed speed.

In summary, we have measured several novel properties of *pin*-doped MQW diodes as photodetectors. The most unusual is the device's ability to function as a wavelength-selective, voltage-tunable photodetector, which should allow precise simultaneous measurement of an optical beam's wavelength and intensity. We have demonstrated a wavelength precision of 0.03 Å, which is considerably better than that possible with other solid-state techniques.[3] The device is all solid state, fast, compact, and suitable for integration with source and detector components.

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