77 K far-infrared hot-electron multi-quantum-well detectors

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The responsivity to long wavelength (513 and 1253 μm) far-infrared (FIR) radiation and the root mean square noise voltage has been measured for one bulk GaAs and two GaAs/AlGaAs multiquantum-well (MQW) hot-electron photodetectors as a function of temperature from 4.49 to 77 K. From these data the noise-equivalent power (NEP) was determined for each device over the same temperature range. The MQW detectors were measured to have 77 K responsivities and NEPs that were one to two orders of magnitude better than those measured using the high purity bulk GaAs sample. To the best of our knowledge, these are the first measurements which show that hot electron MQW detectors are able to outperform bulk GaAs detectors at 77 K. Furthermore, the photoresponse of the MQW structures showed a much slower temperature dependent rolloff as compared to the bulk device, which implies a potential for applications at temperatures above 77 K. Detection of nanosecond pulses of 496 μm FIR radiation by one MQW detector and the bulk GaAs is additional evidence of hot-electron photoconductivity. © *1998 American Vacuum Society.*
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I. INTRODUCTION

The far-infrared (FIR) is one of the least studied regions of the electromagnetic spectrum. One of the main difficulties in studying it has been the lack of good FIR detectors. However in the last decade interest in the FIR region has increased greatly, necessitating the development of fast, sensitive, and durable FIR detectors for use in a variety of applications, including astronomical observations, radar modeling, and FIR spectroscopy.

At this time there are two classes of ultrafast (response time $<1\times10^{-9}$ s) FIR detectors, junction devices, and nonjunction devices. There are two types of junction devices, Schottky barrier diodes and superconductor–insulator–superconductor (SIS) junctions. Both of them have an extremely fast response time ($\tau_R\approx10^{-12}$ s) and are reasonably sensitive. Unfortunately, Schottky diodes and SIS junctions require sophisticated fabrication techniques and are notoriously fragile. The second class of ultrafast FIR detector includes, silicon D-photoconductors,[1] bulk GaAs photodetectors,[2] doped Ge extrinsic photoconductors,[3] superconducting hot-electron bolometers,[4–7] GaAs/(Ga, Al)As multiquantum-well (MQW) structures using donor photoionization,[8] and the subject of this article, the molecular beam epitaxy (MBE) grown, GaAs/(Ga, Al)As MQW structures and bulk GaAs employing free carrier absorption via the hot electron effect.[9,10] While the nonjunction FIR detectors are not as fast ($\tau_R\approx10^{-9}$ s) (Refs. 9 and 10) as the junction detectors they are simpler to fabricate and quite rugged. In this article we briefly report the experimental results of our current research on GaAs/AlGaAs MQW and bulk GaAs hot-electron photodetectors.

II. DEVICE FABRICATION

All the detectors used in this work were grown by one of the authors (W.D.G.) in a 2 in. elemental-source MBE machine at 680 °C, with sample A having an 18% Al concentration and sample B a 35% Al concentration. Arsenic overpressure growth interruptions lasting 5 s were used between the well and barrier layers in order to improve interface morphology. Once grown, the samples were fabricated into photoconductors. The geometry of the bulk GaAs detector is identical to that of the MQWs except that, instead of alternating layers of GaAs and AlGaAs, there is just one 8.7 μm layer of bulk GaAs. The contacts were formed by fabricating dovetail recesses along the $\{0\bar{1}1\}$ planes with a wet etch (to a depth of $\approx75\%$ of the layer thickness), evaporating Ni/Ge/Au into the recesses, and annealing the device at 450 °C for 30 s in a N_2 atmosphere. The oversized device was then cleaved into its finished size of 6×6 mm, and gold wires were attached using a conducting epoxy. The contacts were specifically designed to cover the lower portion ($\{1\bar{1}1\}$ and $\{\bar{1}11\}$ *B* planes) of the dovetails. Illustrations of the detector geometry and a diagram of the conduction band including the doping position can be found in Ref. 11. A summary of the relevant parameters of the MQW and bulk GaAs detectors is provided in Table I.

III. EXPERIMENTAL PROCEDURE

A. Detector responsivity and noise measurements

A CO_2/FIR laser system is used to produce a beam of coherent FIR radiation which is used to measure the responsivity and the noise-equivalent power (NEP) of the photoconductive detectors used in this work. A complete descrip-

TABLE I. Sample parameters of the MQW and GaAs detectors. (N/A—not available.)

Sample No.	Well width (Å)	Barrier width (Å)	Number of wells	Doping level donors/cm^{-3}
3-1968A	170	300	50	1.0×10^{16}
3-1993A	280	300	50	3.5×10^{15}
3-2580C	N/A	N/A	N/A	1.0×10^{15}

tion of the experimental system including illustrations can be found in Ref. 12. The FIR beam is modulated at 200 Hz by a beam chopper, collimated, and focused down onto the input window of either a LHe Dewar or a power meter, and a reference bolometer using two lenses and a beam splitter. The reference bolometer response voltage is displayed on a lock-in amplifier (LIA) and recorded along with its corresponding power meter reading. By doing this the incident laser power can be obtained at any time during the experiment by simply multiplying a subsequent reference voltage reading by the ratio of the original reference voltage and power meter readings. When the power measurement is complete, the power meter is replaced by a MQW or bulk GaAs sample mounted inside the Dewar and cooled to ≈LHe temperatures. The sample is illuminated by FIR radiation and the bias voltage and load resistance are adjusted to optimize the detector's response. The response voltage is the observed on a LIA and recorded. The response voltage is then divided by the incident power to obtain the MQW or bulk GaAs sample's responsivity in volts per watt to this particular far-infrared wavelength. After the responsivity measurement is made the noise level is measured. This is done by blocking the input window on the Dewar containing the sample under test, thus preventing any radiation from illuminating the sample. The bias voltage and load resistance remain at the same values they were at for the responsivity measurement. Then the gain on the LIA is increased as much as possible without overloading, and 200 noise voltage data points are recorded. The root mean square (rms) value calculated for the data set defines the rms noise voltage. This quantity is then divided by the corresponding responsivity to obtain the NEP, which may be defined as

$$\mathrm{NEP} \equiv \frac{\text{noise voltage (rms)}}{\text{responsivity}}. \tag{1}$$

The Dewar that houses the MQW or bulk GaAs sample also has a temperature control system installed in it. This will provide a method of measuring the responsivity and NEP as a function of temperature at a particular wavelength from 4.49 to 77 K. This procedure is repeated for two wavelengths 513 and 1253 μm. In this way the MQW or bulk GaAs sample's responsivity to continuous wave (cw) radiation and the NEP as a function of wavelength and temperature is obtained.

From the very beginning of this work, it was assumed that the MQW samples were much noisier than the bulk GaAs due to poor ohmic contacts. This makes the comparison of the measured NEP values between the MQWs and the bulk GaAs somewhat unfair because noisy contacts are a manufacturing problem and not a fundamental physical property of the MQWs. Hopefully, this is a problem that can eventually be solved. To make the comparison of NEP values more fair an ''adjusted'' NEP was obtained by using the (200 Hz) bulk GaAs rms noise voltage at a particular temperature and dividing it by the (200 Hz) responsivity of the MQW measured at about the same temperature. To justify the assumption of poor contacts the following experiment was performed. The noise level as a function of frequency or noise spectrum was measured from 20 Hz to 1 MHz at the same selected temperatures that the responsivity and NEP measurements were made. With the input radiation blocked off, the bulk GaAs or MQW sample was set at the values of temperature, bias voltage, and load resistance that corresponded to the selected temperature. The output noise voltage was amplified by a low-noise preamplifier and fed into a spectrum analyzer. The data from the spectrum analyzer were recorded and displayed using a computer. The acquisition of the noise spectra provides information about the type of noise exhibited by a particular sample. If the assumption that the MQWs have poor ohmic contacts is true, then the results of this experiment should show that the MQWs are not only much noisier than the bulk GaAs but their noise spectra exhibits the $1/f$ character indicative of poor contacts.

B. Detection of pulsed radiation

A hybrid transverse-excited atmospheric-pressure (TEA) CO_2 pulsed laser is used to pump a FIR waveguide laser cell which in turn produces a fast [≈13 ns full width at half maximum (FWHM)] and intense pulse of FIR using a cavity-dumping technique. A complete description of the system can be found in Ref. 12. The FIR pulse is then focused down onto a Schottky diode and the MQW or bulk GaAs sample by using a beam splitter, an off-axis parabolic focusing mirror, and a fast lens. The photoconductive response (PR) to the FIR pulse from one detector or the other is displayed and recorded on a Tektronix SCD-5000 digitizing oscilloscope/camera system. Unfortunately the SCD-5000 cannot record data from more than one source simultaneously. The performance of the system was monitored by observing the PR of the Schottky diode on an Tektronix 2467B/DCS01 oscilloscope. A computerized data acquisition system was used for collection and permanent storage of the data. These measurements were performed at a wavelength of 496 μm over the same temperature range as the cw measurements.

Once the data were collected and stored, the rise time and the FWHM for each PR pulse were determined using a computer program designed for that purpose. The rise time of the PR pulse is the interval between the occurrence of the 10% and 90% values of the detector peak response. The true response time of the detector is defined as

$$(\tau_R^2)_{\text{system}} = (\tau_R^2)_{\text{laser pulse}} + (\tau_R^2)_{\text{detector}}, \tag{2}$$

with $(\tau_R)_{\text{system}}$=to the rise time of the PR pulse.

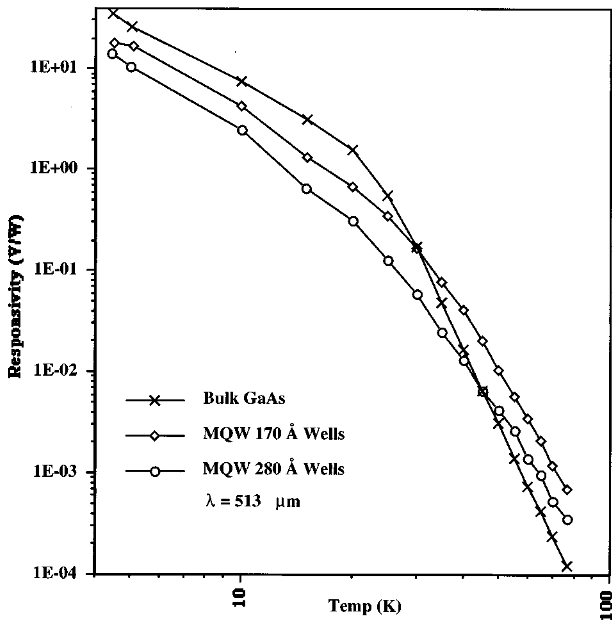

FIG. 1. Responsivity vs temperature at $\lambda = 513$ μm. The lines are to guide the eye.

IV. RESULTS AND DISCUSSION

A. Responsivity versus temperature measurements

Responsivity versus temperature, $R(T)$, was measured for bulk GaAs and both MQW samples at two FIR wavelengths, 513 and 1253 μm. Figure 1 shows a plot comparing these data for all three samples at 513 μm. Figure 2 shows a similar plot of the data taken at 1253 μm. The fact that all of the samples responded to FIR at these wavelengths points very strongly to hot-electron photoconductivity as the detection mechanism, 513 μm is well beyond the long wavelength cutoff point of 400 μm (Refs. 2 and 13) for excited state ionized impurity photoconductivity and 1253 μm is so far past the cutoff point that it eliminates this as a possible detection mechanism. Comparison of the responsivity versus temperature data taken at each wavelength, as shown in Figs. 1 and 2, indicates that all three devices show a greater responsivity to the longer wavelength, at all temperatures. Increasing responsivity with increasing wavelength is consistent with photoconductivity due to hot-electron free carrier absorption.[14]

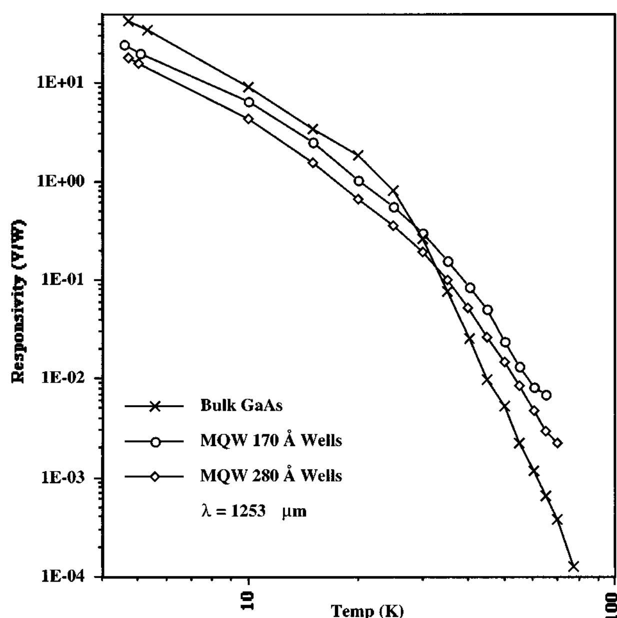

FIG. 2. Responsivity vs temperature at $\lambda = 1253$ μm. The lines are to guide the eye.

At low temperatures bulk GaAs has greater responsivity than the MQW samples. At about 30 K the responsivity curves begin to cross and at $T \geqslant 50$ K the responsivity of the MQWs is better than that of bulk GaAs. From these plots it is apparent that the responsivity falls off with temperature more rapidly in the bulk GaAs than in the MQWs. Not only does the responsivity fall with temperature more slowly for the MQWs than for bulk GaAs, but the responsivity of a MQW is actually greater at $T > 40$ K. This is particularly interesting when viewed in terms of the thickness of the active donor doped regions of GaAs in each sample. Bulk GaAs has an active layer 8.7 μm thick. The MQWs have active regions of $280\,\text{Å} \times 50 = 1.4$ μm and $170\,\text{Å} \times 50 = 0.85$ μm, respectively. Therefore, the absorption of FIR is greater in the bulk GaAs than in the MQWs, although the absorption is probably not more than 1%–2% in any of the samples. In spite of the fact that the 170 Å MQW has an active layer of GaAs a factor of 10 thinner than the bulk GaAs, it still shows better responsivity at higher temperatures. It would be interesting to see how a MQW that had been grown with enough wells to have an active layer equivalent in thickness to that of bulk GaAs performs in this type of experiment.

B. Noise measurements and NEP determination

The noise spectra obtained for each detector (these spectra can be seen in Ref. 12) show that the MQWs are extremely noisy compared to bulk GaAs. While bulk GaAs displays noise spectra that are practically flat, the noise spectra of the MQWs show severe $1/f$ noise. The noise spectra results justify an approach of ''adjusting'' the low-frequency (200 Hz) NEP values calculated for the MQW samples by using the high-frequency noise voltage, or equivalently, the bulk GaAs noise voltage. This also means that if the MQW contacts cannot be improved better noise performance can be obtained by operating at higher frequencies. The MQW noise spectra flatten out and become equivalent to those of the bulk GaAs at frequencies above 750 kHz. Plots of the NEP versus temperature and the ''adjusted'' NEP versus temperature are shown in Figs. 3 and 4. The adjusted versus temperature plots exhibit the same ''crossover'' behavior at $T > 40$ K that the responsivity versus temperature plots do.

C. Pulsed measurements

Figure 5 shows the photoconductive response of the 280 Å MQW at $T \approx 80$ K to a nanosecond pulse of FIR radiation. The response pulse was inverted to make the analysis easier.

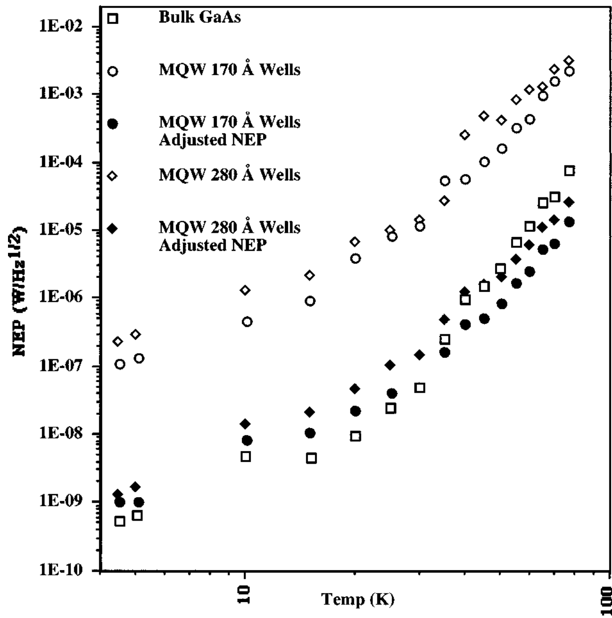

FIG. 3. NEP and adjusted NEP vs temperature at $\lambda = 513$ μm.

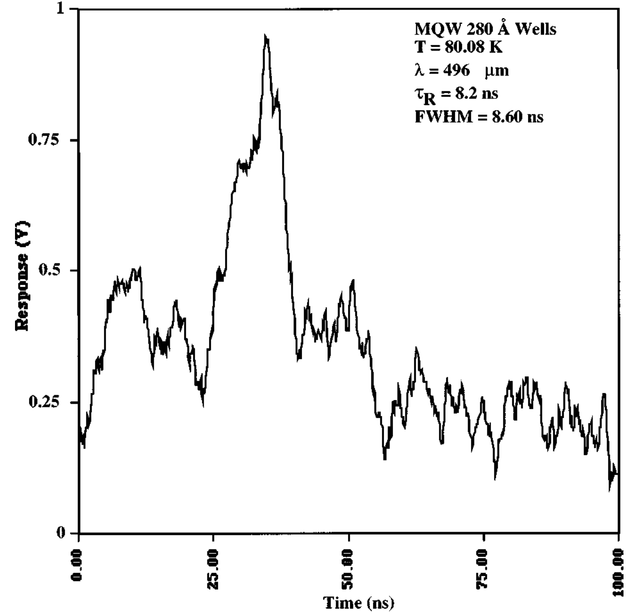

FIG. 5. Photoconductive response of the 280 Å well MQW to a 496 μm FIR pulse.

This plot shows that the MQW detector responds to pulsed FIR up to at least 80 K and has a response time τ_R in at least the nanosecond region. The nanosecond τ_R is further evidence of hot-electron photoconductivity, and completely rules out bolometric effects as the detection mechanism. Furthermore, 496 μm is beyond the long wavelength cutoff point[13] for ionized impurity photoconduction as well. These data present strong evidence for hot-electron photoconductivity being the detection mechanism at work in GaAs/AlGaAs MQWs at high temperatures and long wavelengths.

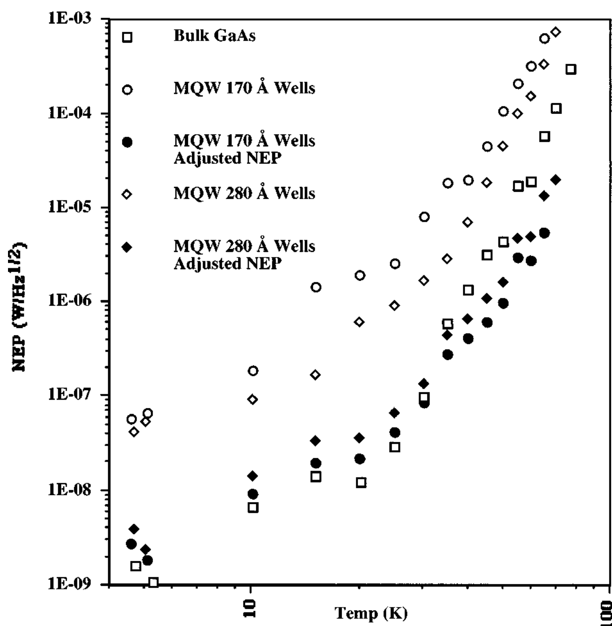

FIG. 4. NEP and adjusted NEP vs temperature at $\lambda = 1253$ μm.

V. CONCLUSIONS

The responsivity and the NEP as a function of temperature was measured for one bulk GaAs sample and two GaAs/AlGaAs MQWs. The noise spectra of each device were also measured from 20 Hz to 1 MHz. The photoconductive response of a MQW to pulsed FIR was also measured as a function of temperature.

These data lead to the following conclusions.

(1) All three devices responded to FIR at wavelengths well beyond the long wavelength cutoff point for ionized impurity photoconductivity, continued to respond to these long wavelengths at temperatures up to 77 K, and showed better responsivity at the longer wavelength. One of the MQWs responded to nanosecond pulses of FIR indicating τ_R's in at least the nanosecond range. These characteristics are consistent with free carrier absorption via the hot-electron effect as the detection mechanism.

(2) If the sources of the observed $1/f$ noise spectra of the MQWs can be eliminated, then the MQW detectors should approach the same noise level as the bulk GaAs detectors. It is expected that improved ohmic contacts to the GaAs wells will remove much of the low frequency noise.

(3) If the MQWs were constructed with enough wells so that the active layer of GaAs was equivalent to that of bulk GaAs, they might perform at least as well in terms of responsivity and NEP at temperatures below 40 K. A MQW with more wells and good contacts may continue to provide good response to FIR radiation at temperatures above 77 K.

This research has demonstrated that GaAs/AlGaAs

MQWs have the potential to be developed into fast, sensitive, and rugged detectors of both cw and pulsed FIR radiation at temperatures above that of LN_2. These detectors could have future applications in radio astronomy, atmospheric physics, radar modeling, and spectroscopy.

ACKNOWLEDGMENT

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