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Terahertz photoresponse of quantum wires in magnetic fields

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We have investigated the terahertz photoresponse of quantum wires in high magnetic fields, employing intense far-infrared (FIR) radiation from the UCSB Free-Electron Lasers. Both GaAs-based and InAs-based quantum wires, with widths ranging from 50 nm to 1 μm, were studied. At high FIR power we observed Shubnikov–de Haas type oscillations in photoresponse versus magnetic field, B, resulting from non-resonant electronic heating; the oscillations were much more pronounced than those in resistance versus B. At low FIR power we observed resonant peaks due to magnetoplasmon excitations, whose strength shows strong polarization-dependence and whose energy extrapolates to a finite value at zero B. These results provide a powerful tool for characterizing 1D electronic states in quantum wires.

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1. Introduction

Semiconductor nanostructures driven by intense terahertz (THz) electric fields provide a new and exciting field of study. The intense electric fields are expected to strongly modify quantum-confined 1D and 0D states, and induce various non-linear optical and transport properties. Although linear far-infrared (FIR) spectroscopy using weak FIR radiation has been extensively and successfully used to determine confinement

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potential profiles and excitations in many systems [1], there have been few studies to understand the behavior of quantum wires and dots in the presence of intense FIR laser radiation. Here we report an example of the interaction of strong FIR radiation with quasi-1D electrons. To probe this interaction we studied the response of quantum wires to intense radiation from the UCSB Free-Electron Lasers (FEL) in the frequency range between 0.15 and 5 THz (2 mm–60 μm or 0.6–20 meV).

2. Samples and experimental methods

We have studied two types of quantum wires. Samples 1–3 are edge quantum wires grown on (111)B microfacet structures directly fabricated on patterned GaAs substrates [2]. The widths of these samples are: sample 1, 50 nm; sample 2, 70 nm; and sample 3, 80 nm. Samples 4–6 are etched quantum wires made from InAs/$Al_{0.5}Ga_{0.5}Sb$ single quantum wells [3] with widths of: sample 4, 100 nm; sample 5, 550 nm; and sample 6, 630 nm. The unpatterned structure of samples 4–6 consists of a 15-nm wide InAs well sandwiched between $Al_{0.5}Ga_{0.5}Sb$ barrier layers. The wires were driven by THz radiation from the FEL. We passed a small (< 10 μA) constant current through the sample and measured the change in the voltage across the sample induced by the THz radiation. Magnetic fields up to 9 T were applied perpendicular to the wire plane to vary energy levels in the quantum wires, and all the measurements were made as a function of magnetic field, B.

3. Experimental results and discussion

Figure 1A and B are plots of resistance (in the absence of THz radiation) and THz photoresistance versus B for high FEL power for two different samples: sample 3 at an FEL frequency of 84 cm^{-1}, and sample 6 at a frequency of 22 cm^{-1}, respectively. Strong oscillations in photoresistance can be seen in both traces. The B values where peaks and valleys occur in photoresistance are independent of the FEL frequency; they are determined by the resistance oscillations. A peak (valley) in resistance coincides with a valley (peak) in

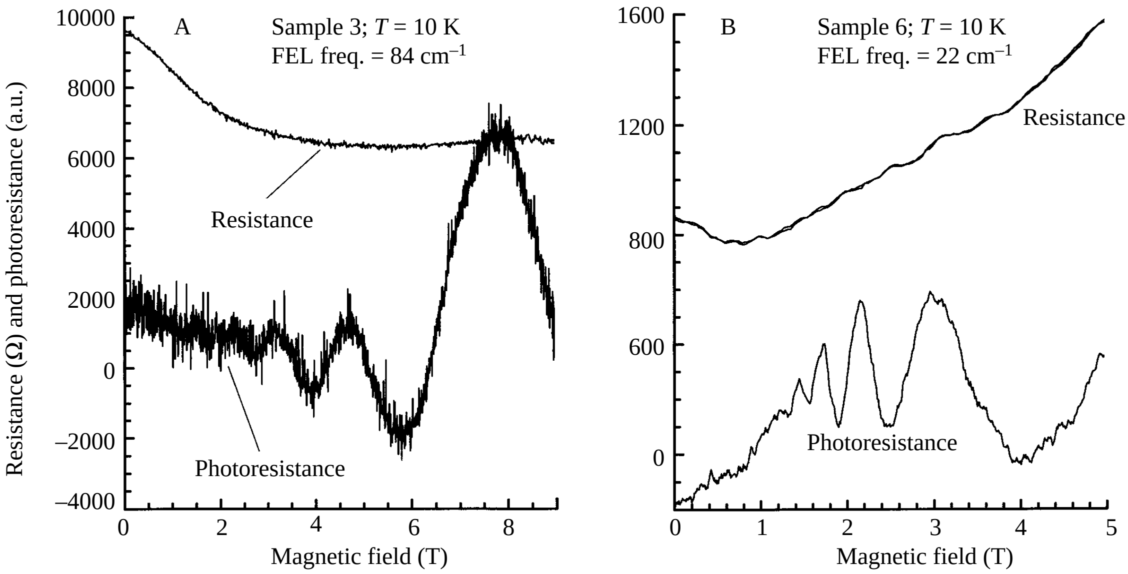

Fig. 1. Resistance and photoresistance at $T = 10$ K as a function of magnetic field at high FEL power for (A) sample 3 at an FEL frequency of 84 cm^{-1} and (B) sample 6 at a frequency of 22 cm^{-1}. Oscillations in the photoresistance are much more pronounced and easier to detect than the resistance oscillations, particularly at low magnetic fields.

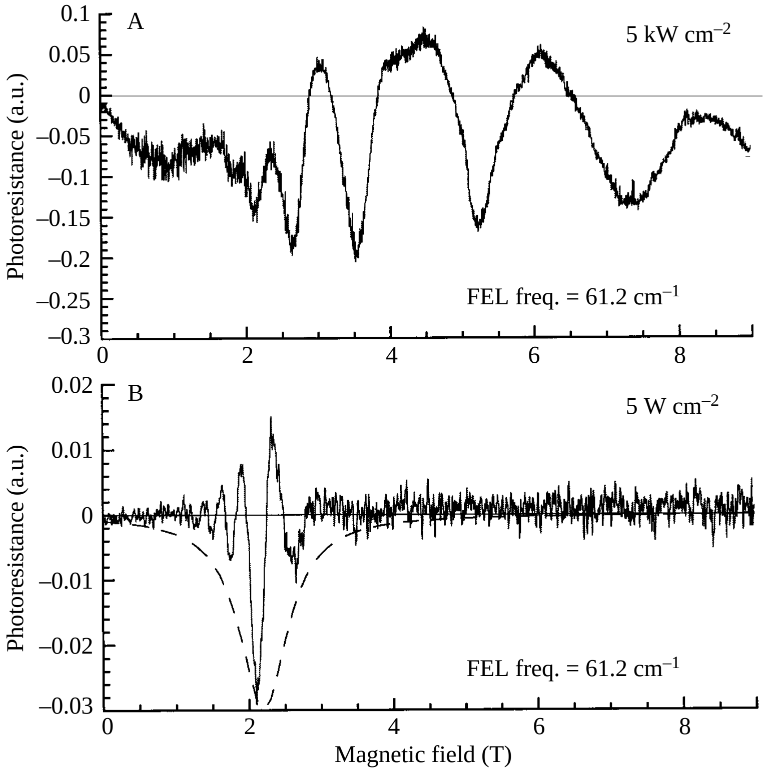

Fig. 2. Photoresistance as a function of magnetic field for sample 5 at an FEL frequency of 66 cm^{-1} for two different FEL powers: (A) 5 kW cm^{-2} and (B) 5 W cm^{-2}. With low power the radiation resonates with the magneto-plasmons in the quantum wires. The resonance (– – –) is modulated by the Shubnikov–de Haas type oscillations.

photoresistance. This suggests non-resonant heating of the electron gas in the wires by FEL radiation as the cause of the photoresistance oscillations; the photoresponse is proportional to the temperature-modulation of the resistance of the wires. It should be noted that the photoresistance oscillations are much more pronounced and, thus, easier to detect, than the resistance oscillations, particularly at low B. This is extremely important since useful information on the wire potential profile can be obtained only at low B, where electric and magnetic confinement are comparable.

Figure 2A and B show how these oscillations depend on the FEL power for sample 5 for an FEL frequency of 61 cm^{-1}. At high power there are noticeable oscillations for the whole range of B. As we lower the power, the non-resonant heating becomes weaker, and the range of B where the oscillations are observable becomes narrower. At the lowest power we find a resonant peak (2.2 T for this FEL frequency), whose envelope is modulated by the Shubnikov–de Haas type oscillations (see Fig. 2B). Unlike the peaks and valleys appearing at high FEL power due to non-resonant heating, this resonant peak shifts with the FEL frequency.

The FEL frequency dependence of the resonant peak, shown in Fig. 3, can be well understood by attributing the peak to magneto-plasmons in the quantum wires [4]. At high B, where the cyclotron radius is expected to be much smaller than the wire-width, the peak approaches 2D cyclotron resonance (CR) having an effective mass of about $0.035m_0$ (this value is consistent with other reports on 2D CR in InAs wells with similar well-width and density [5]). As we decrease the FEL frequency, the peak shifts to lower B following the relation $\omega = (\omega_0^2 + \omega_c^2)^{1/2}$, where $\omega_c = eB/m^*$ is the cyclotron frequency, extrapolating to ω_0 at zero B. The zero-field transition energy ω_0 contains information on the shape of the wire confinement potential, having

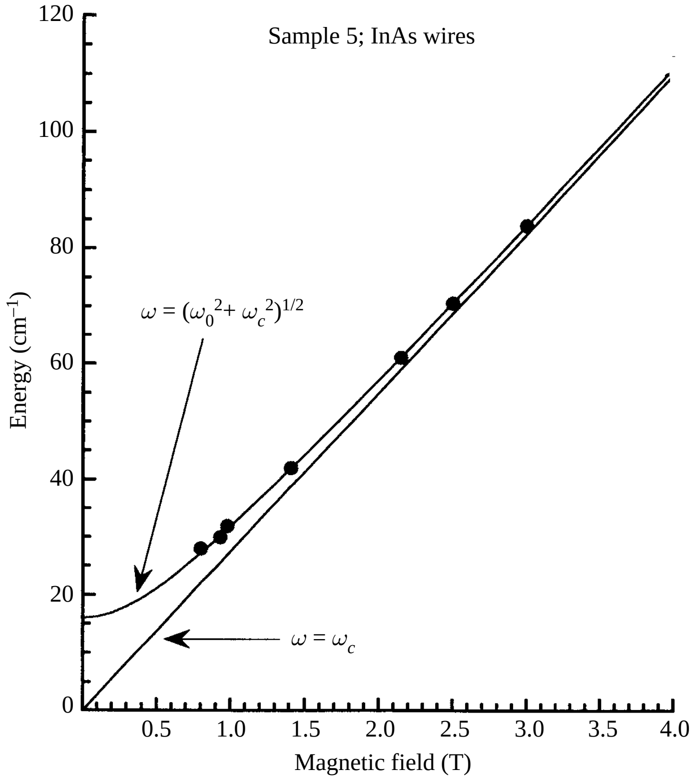

Fig. 3. Resonance frequency versus B for magneto-plasmons observed in sample 5 (InAs quantum wires). The solid straight line represents 2D electron cyclotron resonance with an effective mass of $0.035m_0$. The zero-field intersect, 17 cm^{-1}, corresponds to the plasmon resonance in the wires.

the form $\omega_0 = (\omega_b^2 + \omega_p^2)^{1/2}$, where ω_b is the bare potential and ω_p is the frequency of the plasma oscillation of the electron gas perpendicular to the wire direction. For sample 5, $\omega_0 = 17$ cm^{-1} is deduced from Fig. 3. More detailed discussion on the confinement energies of sample 5 can be found in a separate publication [6].

4. Conclusions

The terahertz photoconductivity method used has been shown to be effective in characterizing quasi-1D states in quantum wires in two distinct but complementary ways: (1) at high FEL powers ($>$ 1 kW cm^{-2}) non-resonant heating results in Shubnikov–de Haas type oscillations that are much more pronounced than magneto-resistance oscillations (especially at low magnetic fields), and caused by a temperature modulation of the electron gas and (2) at low FEL powers ($<$ 5 W cm^{-2}) resonant absorption occurs due to magneto-plasmon excitations in the wires, which results in resonant photoresponse peaks, whose envelopes are modulated by the Shubnikov–de Haas type oscillations. Finally, we note that this method can be used to study a few wires or even a single quantum wire, for which the usual transmission technique fails.

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