A Cold Electron Bolometer using a Two-Dimensional Electron Gas Absorber

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***Abstract*—We describe a new type of Terahertz (THz) detector using a two-dimensional electron gas (2DEG) hot electron bolometer [1] where the temperature of the electrons read out using superconducting tunnel junctions connected to the 2DEG (similar to a SINIS detector). We present measurements of the electron-phonon thermal conductivity in a high-mobility GaAs/AlGaAs 2DEG sample at 4.2 K as a function of electron temperature and magnetic field. From these measurements we estimate the sensitivity of an element in a filled array of S-2DEG-S detectors at 4.2 K to be approximately 10**$^{-14}$ $W/\sqrt{Hz}$ **with a response time of 1 ns. Using measured parameters for the normal resistance of the S-2DEG-S contacts, we calculate the effect of using a voltage bias to cool the electrons in the absorber significantly from a 300 mK base temperature. In this configuration, these detectors can achieve sufficient sensitivity to detect individual THz photons.**

I. Introduction

The next generation of space instruments for FIR/THz astronomy will require a new detector technology that combines (i) sensitivity, (ii) speed, (iii) linearity, (iv) multiplexability and (v) can easily be fabricated in large-format filled arrays. For this reason, several groups are developing new generations of ultra-sensitive detectors such as bolometers using Silicon Nitride thermal isolation and transition- edge superconducting thermometers (TES) (e.g. SRON private communication) or superconducting Kinetic Inductance Detectors (KIDs) (e.g. Mazin, et al., SPIE or Doyle, these proceedings).

Here, we describe a new type of THz detector similar in design to the cold electron bolometer (CEB) consisting of sub-micron size normal metal absorber capacitively coupled via Normal metal/Insulator/Superconductor (NIS) tunnel junctions [2]. We find that using a 2-dimensional electron gas (2DEG) instead of the normal metal strip as the absorbing medium allows (i) simultaneous optimisation of the thermal and electrical properties of the absorber by modification of the electron density and mobility in the 2DEG, (ii) $\simeq 10^5$ times lower thermal conductivity per unit area than in a normal metal absorber for the same impedance and therefore do not require sub-micron dimensions to have good sensitivity. For these reasons, 2DEG CEBs or HEBs are a good candidate for filled arrays of ultra-sensitive bolometers with free-space absorbers (not requiring antennas).

The thermal and electrical properties of electrons in 2DEGs have been measured at low temperatures by a variety of methods ([3], [4])We present precise measurements of the electron-phonon coupling in a high mobility 2DEG sample using multiparameter fits to the Shubnikov-DeHaas oscillations of conductivity vs. magnetic field. From these fits, we estimate the sensitivity of a 2DEG bolometer vs. temperature.

The structure of our sample 2DEG is similar to the 2DEG hot electron bolometer (HEB) described by Yngvesson [5]. Layers of doped and undoped GaAs and AlGaAs are grown via molecular beam epitaxy (MBE), a sketch of this is shown in Figure 1. The discrepancy in the layers' Fermi energy levels gives rise to energy barriers between the layers (Fig 2). Such an energy barrier keeps the electrons trapped in the donor layer until we liberate them with a light pulse. These electrons are bumped into a two-dimensional energy well that lies in the undoped buffer layer of GaAs; they lack sufficient energy to escape this well and are trapped there, forming a 2DEG. The details of the doping and thicknesses of the AlGaAs and GaAs layers determine the mobility and density of carriers in the 2DEG. The mobility is a measure of electrical conductivity per electron and for a high-mobility 2DEG can be thousands of times higher than the conductivity per electron in a metal film. A fixed impedance per square absorber made from a 2DEG requires a much smaller density of electrons per square than a normal metal.

The thermal conductivity between electrons and phonons in an absorber with area, A, at low temperatures follows:

$$G_{\mathrm{ep}} = 5\Sigma n_e A T^4 \tag{1}$$

where Σ, the is a material dependant constant and $n_e A$ is the total number of electrons. The value of Σ for carriers in semiconductors is an order of magnitude smaller than in metals. Therefore, the total electron-phonon conductivity for a 2DEG absorber will be up to 10^5 times lower per unit area than for a metal absorber. A bolometer using a 2DEG absorber is subject to the same equations as more conventional bolometers [6]. Specifically, its NEP^2 is given by the sum of its Johnson,

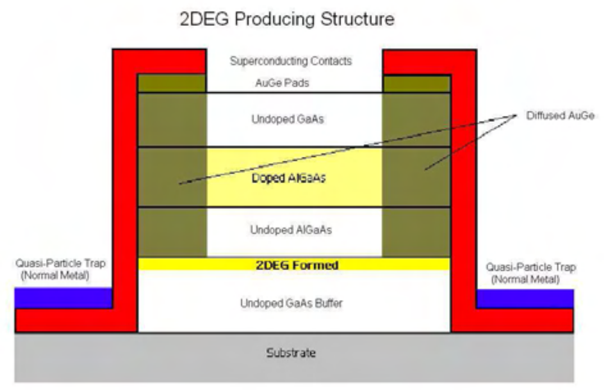

Fig. 1. Cross-sectional sketch of a 2DEG producing structure, not to scale. Shown is what will be our final configuration, with superconducting contacts. We used ohmic contacts for this experiment.

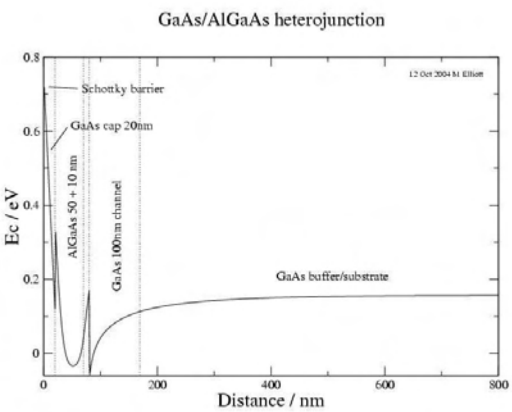

Fig. 2. Schematic of conduction band of semiconductor stack. The Fermi level is indicated by 0 eV.

photon, and amplifier noise. For the sake of this experiment, we are looking at the phonon noise exclusively:

$$NEP^2_{phonon} = 4k_BT_e^2G \tag{2}$$

Where T_e is the electron temperature and the thermal conductivity of the electron gas $G = IV/T_{electron} - T_{lattice}$. IV is the power dissipated in the 2DEG. Determination of the zero magnetic field electron temperature is determined by zero field IV and resistance vs. temperature curves. A resistance vs. temperature curve for a 2DEG shows that the resistance increases linearly according to the equation $R = R_o + \alpha T_e$, where $\alpha = dR/dT$. We have found through experiment that our α is about 3.4 Ohms/Kelvin and our baseline resistance about 115 Ohms.

To determine the electron-phonon thermal conductivity in our 2DEG sample , we measured the electron temperature as a function of the power dissipated in the 2DEG. At low temperatures, a 2DEG will exhibit Shubnikov de Haas (SdH) oscillations [7]–[15]:changes in the value of resistivity with respect to the magnetic field. We determine the electrical (IV) power dissipated by applying a bias voltage to the 2DEG and a resistor in series. The current running through the system is determined by measuring the voltage drop across the bias resistor and the resistivity of the 2DEG is calculated from this current and the voltage drop across the 2DEG. The tests were done at liquid helium temperature (4.2 K) and the magnetic field swept from 0-12 Tesla. Application of the magnetic field gives rise to Landau levels [10],

$$E_{Landau} = \hbar\left(\frac{eB}{m^*}\right)\left(n+\frac{1}{2}\right) = \hbar\omega_c\left(n+\frac{1}{2}\right), \tag{3}$$

where ω_c is the cyclotron frequency. The widths of the Landau levels are determined by the Heisenberg uncertainty relation for energy, $\Delta E \Delta t \leq \hbar/2$, where the time concerned is the lifetime of an electron in the given energy level. As the field increases, the Landau level spacing increases. In an ideal system, we would be able to operate at a temperature of 0 K, guaranteeing all the electrons in the 2DEG are at or below the Fermi level; hence only electrons at the Fermi level would be available to conduct. As we increase the magnetic field, the Fermi energy level of the 2DEG sees the Landau levels moving past. When the Fermi level is between Landau levels, the system is at a quantum plateau where the longitudinal conductivity and resistivity of the 2DEG are simultaneously zero, so we get no longitudinal voltage drop. If the electrons in the 2DEG are too warm, they will partially occupy many levels above that of the Fermi energy, meaning some electrons will be at the same energy level as a Landau level at all times so the observer won't see any oscillations in the resistivity.

The SdH effect is well described theoretically by the 'Lifshitz-Kosevich' formula in which the oscillatory part of the resistance can be expressed as a Fourier-like expansion [7]–[9],

$$\frac{\Delta\rho_{xx}(T_e, B)}{\rho_0} = \sum_r A_r X_r \exp(-Krm^*T_D/B) \times \cos(2\pi rF/B + \phi_r) \tag{4}$$

where ρ_0 is the zero-field resistance, F is the SdH frequency, related to the 2D electron density n_s by $F = (h/2e)n_s$. The terms A_r and ϕ_r are amplitude and phase factors for each harmonic number r. The electron effective mass m^* is $0.067m_e$ for the GaAs-based 2DEGs examined here, and $T_D = \hbar/2\pi k_B\tau$ is the so-called temperature and is related to the scattering lifetime τ of electrons in the quantised Landau levels. The fundamental constant $K = 2\pi^2 k_B/\hbar m_e e = 1.613 \times 10^31$ T(K kg)$^{-1}$

Central to our experiments is the thermal damping factor [7], [15]

$$X_r = \frac{Krm^*T_e/B}{\sinh(Krm^*T_e/B)} \tag{5}$$

arising from the Fermi-Dirac distribution of states around the Fermi level, and which contains all the temperature dependence of the SdH effect. From this factor, by examining the SdH effect as power is dissipated in the sample, it is possible

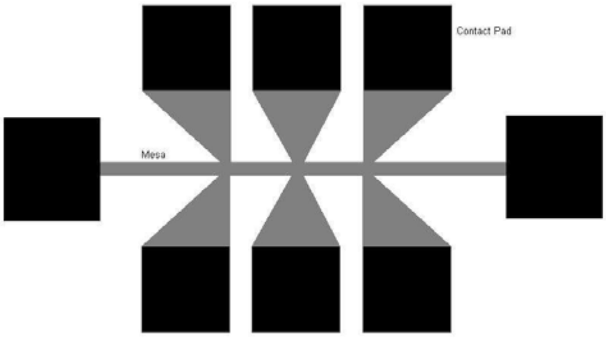

Fig. 3. Sketch of 2DEG mesa structure, not to scale. In our measurements, the bias current was applied via the longitudinal contact pads. The transverse pads were used to measure the longitudinal and transverse (Hall) voltages along the 2DEG.

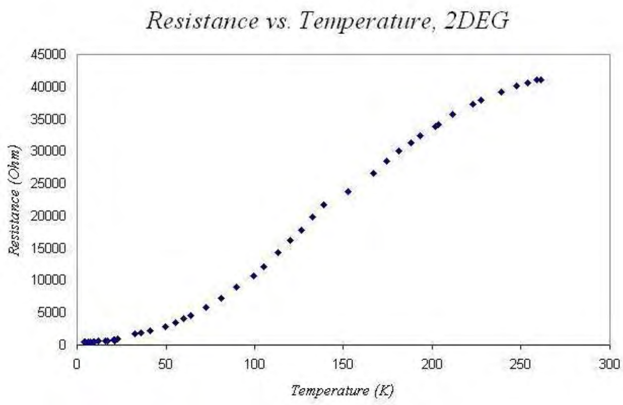

Fig. 4. The resistance of the 2DEG is directly related to its temperature, which rises as the power dissipated in the 2DEG increases, but for low currents, this change is negligible.

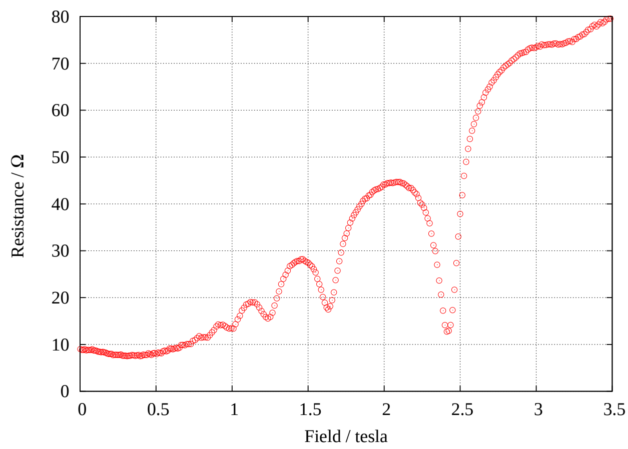

Fig. 5. Field variation of the magnetoresistance of a 2DEG sample at a temperature of 4.22 K for negligible power dissipation.

to calculate the electron temperature T_e, if all other quantities in equation (4) are known.

II. EXPERIMENTAL

Measurements were performed on Hall bars prepared at Nottingham University. The 2DEG sample consisted of the following layers: 170$\AA$ GaAs cap layer, 400$\AA$ silicon-doped AlGaAs layer, 400 $\AA$ AlGaAs spacer layer, 2μm GaAs buffer layer, and a semi-insulating GaAs substrate. The structure was wet-etched to form a mesa. Metallic contacts were added for the sake of applying voltages and reading out. The mesa area was approximately 50×1200μm^2. The longitudinal contact pads are 300×350μm^2, while the transverse pads are 300× 300 μm^2 (see Fig. 3). Standard low-frequency, constant current, four-terminal ac measurements of the longitudinal ρ_{xx} and transverse ρ_{xy} resistance were made at 4.22 K in the bore of a 12 tesla superconducting magnet. We determined the sample power from its resistance and the current (as determined by measuring the voltage V_b across a 100 kΩ series resistor).

Typical low-field SdH oscillations are shown in figure 5. The periodicity of the oscillations corresponds to an electron number density of 2.47×10^{15}m^{-2}, in good agreement with simultaneous measurements of the Hall resistance in this sample, which gave a number density of 2.51×10^{15}m^{-2}. Although oscillations occur up to the highest field measured (the filling factor $\nu = 1$ occurs around 9.5 tesla), detailed analysis of these data is complicated by spin-splitting of the oscillations, and by slight inaccuracies in the Hall bar geometry, so is not presented here.

III. RESULTS AND ANALYSIS

As the resistance of the 2DEG changes, so, too, must the power dissipated within it (Fig. 4); the electron temperature will therefore vary as the magnetic field changes. However, at sufficiently low bias voltages, the change in the electron temperature over the course of the experiment will be negligible, so we take a curve at low fields and fit it with that assumption. From that curve, we find via the fit values for the Dingle temperature, the SdH frequency, the phase factors, and the harmonic coefficients. The two-step analysis process was as follows.

1) First, equation (4) was used to fit the SdH data (with typically 3 to 10 harmonics depending on field range) at sufficiently low current with negligible dissipation, where we can assume that $T_e = 4.22$K, the known temperature of the sample helium bath. This yielded 3-10 amplitudes and phases, a Dingle temperature T_D and a frequency F (also an offset, linear and quadratic term in $\rho(B)$ to allow for the non-oscillatory part of the magnetoresistance).
2) The data at higher dissipation was then analysed, with T_e alone as the adjustable fitting parameter. This is justified for small temperature rises since all other terms are essentially temperature independent.

It is worth pointing out that most theories [9] find the amplitude factors A_r all equal to 4, but Vavilov and Aleiner [8] indicate that this is not generally true, and our experiments confirm that it is essential to use them as fitting parameters

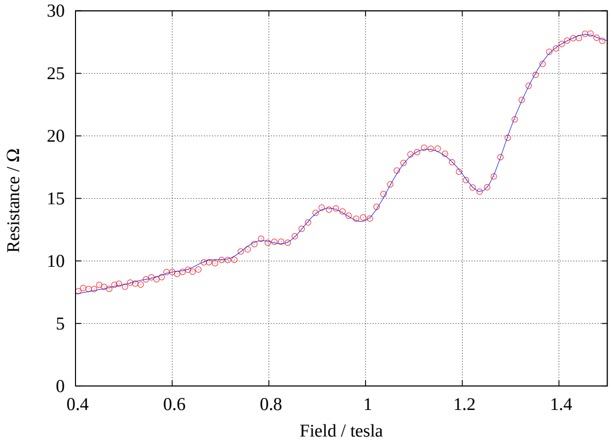

Fig. 6. Analysis of the low-field portion of figure 5. The sample current was approximately 0.23μA. A 4-harmonic fit of equation (4) with fixed temperature 4.22 K. was made, yielding a Dingle temperature T_D=1.17±0.17 K.

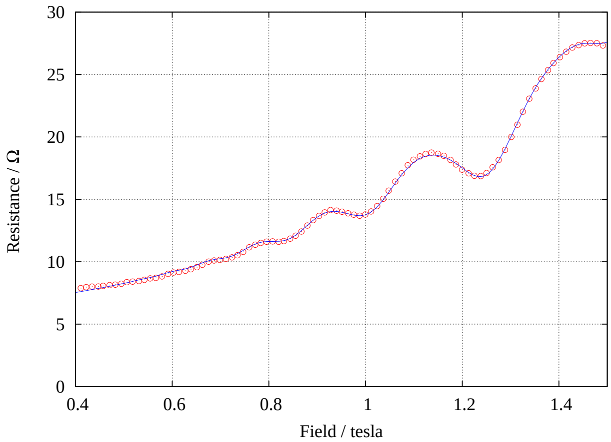

Fig. 7. Analysis of low-field SdH oscillations with a sample current of approximately 5μA. A 4-harmonic fit with $T = 4.76 \pm 0.02$K is shown.

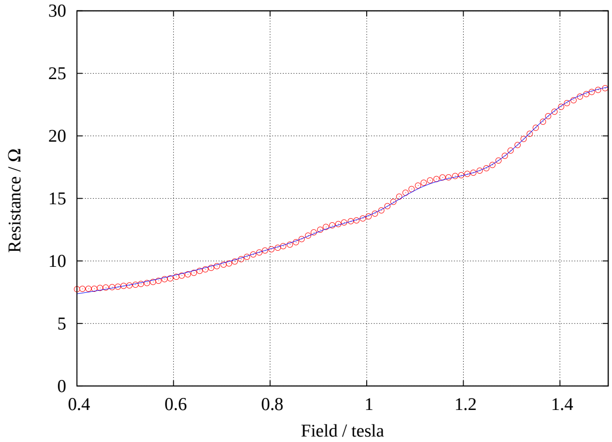

Fig. 8. Analysis of low-field SdH oscillations with a sample current of approximately 10μA. A 4-harmonic fit with $T = 7.01 \pm 0.09$K is shown.

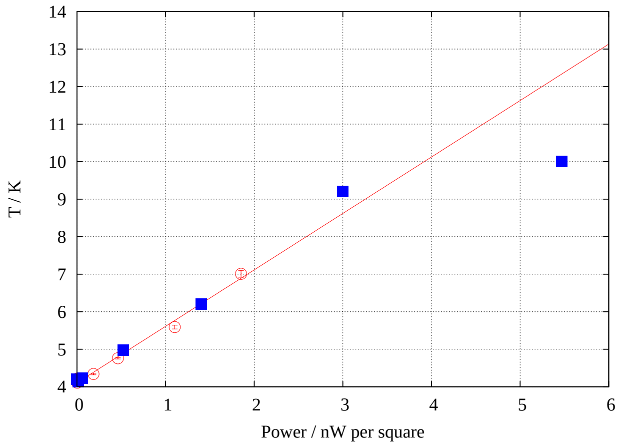

Fig. 9. Electron temperature versus sample power, derived from the low-field SdH fit (red circles) and high-field fit (blue squares). A linear fit 1.50 ± 0.06 K/nW to the low-field points is shown.

to describe the SdH oscillations sasifactorily. Most previous analyses have avoided this issue by using very low-field or higher temperature data, where the harmonic terms are negligible. We also let the phase terms ϕ_r be adjustable fitting parameters, even though they are known theoretically, because they are rather sensitive to magnet hysteresis and error in the field.

In Figure 6 we show the results of Step 1 of the fitting procedure and gives a very satisfactory fit to the SdH data. The Dingle temperature found corresponds to a scattering lifetime of 1.04 ps or 'quantum mobility' $\mu_q = e\tau/m^*$ of 2.73 m^2/Vs.

The results of Step 2 are illustrated in Figures 7 and 8. They show the decrease in SdH oscillation amplitude as the ac drive current through the sample is increased. Excellent fits to the data are produced using the same parameters as obtained in the first fit, but with temperature as the single adjustable parameter. The poorer quality of the fits at higher bias voltages is due to variations in power dissipation that become more acute at higher electron temperatures.

Finally a graph of the temperature rise in the 2DEG as a function of power dissipated. Included are data from high and low magnetic field fits. The greater variations in the resistivity in the high field oscillations mean that the constant electron temperature assumption is less valid there. With the addition of the heating effects at higher currents, the high field data deviates from the trend even more severely. Even so, there is a compelling agreement with low and high field data for lower power dissipation levels (lower currents).

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IV. Conclusion

The resistivity of a 2DEG undergoing SdH oscillations can be very accurately modeled using the 'Lifshitz-Kosevich' formula and assuming that the electron temperature doesn't change with the resistivity. While ignoring electron heating leads to rather poor overall fits at high bias voltages, low field fits are fairly accurate. High field fits are similarly impaired by the assumption of constant electron temperature, but low bias voltage, high field fits agree with the trend evident from the low field data. Our data points to an electron heating rate of 1.50$\pm$0.06 K/nW/square at 4.2 K. A 1 mm^2 2DEG absorber would therefore have an electron-phonon thermal conductance of about 10^{-7} W/K. This absorber used with an ideal electron thermometer would give a detector NEP of approximately $10^{-14}W/\sqrt{Hz}$ with a response time of 1 ns (τ=C/G). By taking into account the area and electron density of our 2DEG, we calculate a G of 5.45$\times10^{-15}$ W/K per electron. This is in good agreement with Appleyard [12], who gets 1.5×10^{-14} W/K per electron. In addition, the low electron-phonon coupling of the 2DEG absorber enables efficient cooling of the electrons well below the lattice temperature through the use of superconductor-2DEG-superconductor contacts. This effect has been shown to work in highly doped thin silicon films [16]. The 2DEGs should work better than silicon due to their higher mobilities and lower densities of carriers. Detectors of this type would potentially have sufficient sensitivity ($10^{-21}W/\sqrt{Hz}$) to resolve individual THz photons. Future work will probe the thermal and electrical properties of the 2DEGs and superconducting contacts at sub-Kelvin temperatures.

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