Magnetotransport measurements on freely suspended two-dimensional electron gases

R.H. Blick∗†, F.G. Monzon∗, W. Wegscheider∗†, M. Bichler∗∗, F. Stern∗∗∗†, and M.L. Roukes∗

∗ California Institute of Technology, Condensed Matter Physics 114-36, Pasadena, California 91125, USA.
∗∗ Walter-Schottky-Institut der Technischen Universität München, Am Coulombwall, 85748 Garching, Germany.
∗∗∗ IBM T.J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598, USA.

(March 21, 2022)

We present magnetotransport measurements on freely suspended two-dimensional electron gases from AlGaAs/GaAs heterostructures. The technique to realize such devices relies on a specially MBE grown GaAs/AlGaAs-heterostructure including a sacrificial layer. We fabricated simple Hall-bars as well as quantum cavities and quantum dot systems. We find well-pronounced Shubnikov-de Haas oscillations and observe commensurability resonances, allowing characterization of the electron gas in these 100 nm thin membranes.

Recently the realization of suspended, monocrystalline, GaAs nanostructures containing a three-dimensional electron gas has been demonstrated [1]. Previous work has shown the possibility of using a GaAs high-electron mobility transistor to achieve sensitive piezoelectric detection of strain [2]. We are combining these techniques to enable new means of detecting motion in nanomechanical systems and to study interactions in coupled electron-phonon systems of reduced dimensionality for both the electrons and the phonons. Free-standing structures incorporating a high-mobility electron gas have interesting device applications: A high mobility 2DEG system provides a unique approach to implement wideband, extremely sensitive displacement detection. These systems also offer prospects for very sensitive bolometers and represent model systems for high sensitivity calorimetry [3]. One very interesting potential application is in heat capacity measurements on two-dimensional electron gases (2DEGs). The sensitivity of these types of thermal devices is enhanced by their small volume, which can be of order of ∼ 3 µm³, significantly smaller than the usual dimensions of ∼ 10⁸ µm³ [1,3].

In this work we discuss the processing technique of such devices and present first results on magnetotransport measurements on suspended two- and zero-dimensional systems. The processing employs a specially-designed MBE-grown 2DEG heterostructure in which a sacrificial layer is included. The layer structure is shown in Fig. 1(a): The structural layer stack, from which the devices are formed, comprises seven individual layers having a total thickness of 100 nm. Top and bottom are formed by thin GaAs cap layers preventing oxidation of the AlGaAs:Si donor layers which follow beneath. The central 15 nm thick GaAs layer forms a quantum well sustaining a high mobility 2DEG located 37 nm below the top surface and is surrounded by two AlGaAs spacer layers. Below the structural layer stack is a 400 nm Al₀.₈Ga₀.₂As sacrificial layer.

The heterostructure was designed by modelling the conduction band lineup numerically. These calculations employed a Poisson-Schrödinger solver program, written by Laux and Kumar, which neglects many-body effects [4]. In contrast to common 2DEG heterostructure configurations, here an additional GaAs layer is included to avoid deleterious carrier depletion effects from the lower surface once it becomes exposed, i.e. after the sacrificial etch. The calculations indicate the donor regions are particularly susceptible to illumination, and that parallel conduction might be possible. However, in our measurements no obvious contribution from such channels even after continuous illumination was evident as will be discussed below. Hence, we only have to consider a single 2DEG layer in the evaluation below.

To realize these suspended nanostructures with three-dimensional relief we employ multiple steps of optical and electron beam lithography, followed by a combination of pattern transfer steps. The latter involve both anisotropic ion-beam (dry) and chemically-selective (wet) etching techniques. The first step of the processing procedure is fabrication of standard Au/Ni/Ge ohmic contacts to the GaAs. These require an annealing step after their deposition. The second step is definition of contacts by optical and electron beam lithography and patterning with Ni. These contacts serve as a metallic etch mask during the subsequent ion-beam etch step. The Ni etch mask is selectively removed by another brief wet etch step employing FeCl₃ after the dry etch. The device geometry is machined by anisotropic, chemically assisted ion beam etching (CAIBE) with chlorine gas. The final step then is the selective chemical etch to remove the sacrificial layer. Depending on the stoichiometry of the structural layer, either a 2% solution of HF or concentrated HCl was employed [5,6].

A typical freely suspended 2DEG samples is shown in Fig. 1(b): In this case the device has a shape similar to a conventional Hall bar with dimensions of 1×2 µm² (width × length). In Fig. 2(a) a scanning electron microscope (SEM) micrograph of the same device as in Fig. 1(b) is shown, but taken at a steeper angle; the sacrificial layer is
clearly seen to be completely removed from beneath the structure. In comparison to usual Hall-bars with a wide 2DEG region and small contact areas we had to choose a simplified design, since the underetching effectively limits the lateral extension of the system. For larger membranes the mechanical supports are commonly undercut as well, leading to a collapse of the whole structure. Although the contact areas are fairly large compared to the device size, the mini-Hall-bar allows us to monitor the longitudinal voltage drop properly.

Our quantum devices, also exemplified in Fig. 2(b), represent the first truly suspended quantum dots. The single dot has a final diameter of 800 nm, while the diameter of the two coupled dots is of order of 400 nm. As discussed below, the actual electronic diameter of these devices is reduced by edge depletion. In the present case, coupling between the dots is mediated by the constriction regions connecting them. Careful design of the geometry of these regions allows to control the carrier depletion and hence the degree of coupling to the leads. Fabrication of additional gate contacts in these regions, not attempted in these preliminary investigations, would permit definition of variable tunneling barriers.

At first, low temperature magnetotransport measurements were carried out to characterize the electron gas in the mini-Hall-bar and the quantum devices. Fig. 2(c) displays Shubnikov-de Haas (SdH) oscillations in the longitudinal resistance for one of the suspended Hall bar samples after illumination with a red light emitting diode for 60 sec. Prior to illumination the resistance commonly was a factor of five larger, as seen in the values obtained for the cavities A and B in Fig. 3. The reason for this deviations might be also found in a varying surface tension of the different suspended 2DEGs. The electron density is finally obtained from the SdH-oscillations shown in Fig. 2(c) through the standard relation \( \Delta (1/B) = g_e e/(h n_s) \), where \( g_e \) is the spin degeneracy factor (here \( g_e = 2 \)), which yields \( n_s \approx 5.5 \times 10^{15} \) m\(^{-2}\). Note that the Landau levels are well developed even at fairly low fields. In the inset of Fig. 2(c) the \((1/B)\) spectrum of the oscillations for the illuminated shows only a single period. Hence, a parallel conduction channel appears to be absent or can at least be neglected for the transport data, despite illumination and the model calculations. The most likely explanation for this is the fact that lattice strain effects are not included in the model calculations, but are expected to play a significant role for these suspended devices.

For the mini-Hall-bar the sheet resistance is of the order of \( \rho = \rho_{xx} \approx 4 \, \text{k}\Omega/\square \) without illumination, and \( \approx 700 \, \Omega/\square \) without illumination, and \( \approx 800 \, \Omega/\square \) after illumination. The values are obtained by extrapolating the resistance values from \( B = 1.5 \, T \) to \( B = 0 \, T \), in order to circumvent contributions by scattering around \( B = 0 \) (seen in the strong negative magnetoresistance). As noted before, the length/width ratio of the Hall bars is \( l/w = 2 \, \mu m/1 \, \mu m = 2 \). Combin-
ically defined size of 800 nm, we thus find a depletion depth of ~175 nm from the edges. The fact that AB-like oscillations are found without an opening in the center could possibly be explained by some local inhomogeneity within the dot, e.g. local strain in the 2DEG, which might result in an effective depletion of the electrons in the center of the cavity. This also agrees with the disappearance of AB oscillations after illumination (higher density). Apart from the peculiarity of the existence of AB-oscillations in such a sample it has to be noted that dissipation phenomena in free-standing 2DEGs seem to be less pronounced than in comparable 2DEGs connected to the bulk GaAs-crystal.

The electronic radius found from the AB like oscillations is confirmed by the coarse modulation, which can be explained by geometric resonances found earlier in strongly modulated one-dimensional electron systems. From this model we obtain the classical cyclotron radius \( r_\text{c} = \frac{\hbar k_F}{eB} \) with \( k_F = \sqrt{2m_\text{F} \pi n_\text{F}} \) being the Fermi wave vector. For the two quantum cavities measured (Fig. 3) we find a variety of different radii: For the first cavity A (Fig. 4(a)) we obtained \( r_\text{c} = 652 \text{nm}, r_\text{c}^d = 680 \text{nm}, r_\text{c}^b = 484 \text{nm}, r_\text{c}^b = 357 \text{nm}, r_\text{c}^b = 265 \text{nm} \) after illumination. Prior to illumination the only cyclotron orbit found is \( r_\text{c} = r_\text{c}^c \). Similar commensurability oscillations and an almost identical fine structure are found for cavity B (Fig. 4(b)): \( r_\text{c}^c = 874 \text{nm}, r_\text{c}^b = 539 \text{nm}, r_\text{c}^b = 210 \text{nm} \). The insets in Fig. 4(a,b) show some of the possible orbits: The upper sketch \( \alpha \) shows the ideal case, while in the lower one (\( \beta \)) we allowed a finite contact width, demonstrating the occurrence of the different cyclotron radii. In the third case \( \gamma \) the electron follows a trajectory with maximum cyclotron radius (with non-ideal contacts), elucidating the large values of 600 – 800 nm measured. Considering the different radii and the corresponding orbits we obtain for the smallest radii A: \( r_\text{c}^a = 265 \text{nm} \) and B: \( r_\text{c}^a = 210 \text{nm} \) a reasonable agreement with the values obtained before under the assumption of AB oscillations. Since we find similar radii for the commensurability oscillations, being caused by the coarse modulation, and under the assumption of AB-oscillations, caused by the fine structure, we are confident that the depletion depth is correctly determined.

Finally, we want to present some of the first transport data on suspended quantum dots as shown in Fig. 2(b), i.e. for the case when \( G < e^2/h \). Already strong indications were found that the relaxation mechanisms of single electrons tunneling through coupled dots is influenced by discrete phonon modes. However, these quantum dots were still embedded in the bulk GaAs crystal and hence the phonon coupling is not well controlled. The conductance measurements on a quantum dot under bias voltage strongly decoupled from the leads are shown in Fig. 5. For these measurements we employed the coupled dot system shown in Fig. 2(b), since the smaller total size and the narrower contacts result in an increased resistance. As seen we find a transition into the tunneling regime for \( B = 0 \text{ T} \) in the low drain/source bias (\( V_{ds} < \pm 75 \text{ mV} \)) regime where the conductance \( G = dI/dV \) is found to be below \( e^2/h \). The conductance drops below \( e^2/h \) for bias voltages around +20 mV to +50 mV. This drop is found to occur stepwise. Including the magnetic field dependence we are able to identify three different step widths, which are denoted \( E_1^0, E_1^1, \) and \( E_1^2 \). Interpreted as charging states of the quantum dots these steps correspond to energies approximately 40 meV, 10 meV, and 30 meV, respectively. A crude estimation of the charging energy expected from the electronic dot radius of roughly \( r_\text{c} \sim 200 \text{ nm} \) (using the values found above for the depletion depth) we obtain \( E_C = e^2/2C_\Sigma \sim 1 \text{ meV} \). We assumed a dielectric disk with \( C_\Sigma = \varepsilon_0 \varepsilon_r r_\text{c} \), where \( C_\Sigma \) is the total capacitance of the dot, \( \varepsilon_r \) the dielectric constant of AlGaAs and \( \varepsilon_0 = 8.85 \times 10^{-12} \text{ F/m} \). Although this value is far below the stepsize found in Fig. 5, it is still sufficient to allow Coulomb blockade (CB) at 4.2 K. Moreover, it is possible that the electronic diameter of the coupled dots is smaller than we estimated here.

Unfortunately it was not possible to verify charging of the quantum dot device by an external gate directly. Thus no clear CB signature can be identified for this device. Instead we applied a magnetic field perpendicular to the plane of the dot. Increasing the field, we observe a suppression and an additional modulation of the conductance around \( V_{ds} = 0 \), as seen for \( B = 4 \text{ T} \) and 8 T. Discrete states in the quantum dot must have formed, indicated by the structure in the IV-characteristic of Fig. 5. This is evidenced by the modulation at finite magnetic field. Additionally, we find an enhanced background noise when keeping the dots under forward bias, which can be attributed to an effective mechanical vibration of the whole sample, due the resulting Lorentz force in the magnetic field.

In summary, we have demonstrated a technique of how to fabricate freely suspended two-dimensional electron gases. In transport measurements we observe the characteristic features of 2DEGs. Moreover, we find at low temperatures a strong negative magnetoresistance effect, indicating the lower mobilities of the suspended electron gas compared to the bulk values. In further measurements on suspended quantum dots and quantum cavities we found geometric resonances and a fine structure from which we estimate the lateral depletion length to be 175 nm. Finally, we presented first measurements of transport spectroscopy on a suspended quantum dot structure revealing the existence of discrete states. Although the properties of the suspended electron gas are not yet optimized in comparison to conventional AlGaAs/GaAs heterostructures, we clearly demonstrated functioning of these devices. Moreover, this technique offers a broad variety of possible applications, including high-frequency strain sensing in nano-mechanical devices, studies on
the single electron/phonon interaction, measurements of 
electronic specific heat and ultra-sensitive bolometry.

We gratefully acknowledge funding for this work from 
DARPA MTO/MEMS under grant DABT-63-98-1-0012. 
We thank A.N. Cleland for expert technical help and S. 
Ulloa for critically reading the manuscript. RHB thanks 
the Max-Planck-Gesellschaft (Otto-Hahn stipend), the 
Max-Planck-Institute for Solid State Physics, Stuttgart, 
and the Alexander-von-Humboldt Stiftung (Feodor-
Lynen stipend) for support.

† current address: Center for NanoScience and Sektion 
Physik, Ludwig-Maximilians-Universität München, 
Geschwister-Scholl-Platz 1, 80539 Munich, Germany. 
e-mail: robert.blick@physik.uni-muenchen.de

‡ new address: Institut für Angewandte und Experimentelle Physik, Universität Regensburg, 93040 Regensburg, Germany.

IBM Research Staff Member Emeritus.

[1] T.S. Tighe, J.M. Worlock, and M.L. Roukes, Appl. Phys. 
Lett. 70, 2687 (1997).
[2] R.G. Beck, M.A. Eriksson, R.M. Westervelt, K.L. Camp-
man, and A.C. Gossard, Appl. Phys. Lett. 68, 3763 
(1996); R.G. Beck, M.A. Eriksson, R.M. Westervelt, K.L. 
Campman, and A.C. Gossard, Appl. Phys. Lett. 73, 1149 
(1998).
[3] K. Schwab, E.A. Henriksen, J.M. Worlock, and M.L. 
Roukes, Nature 404, 974 (2000).
[4] A. Kumar, S.E. Laux, and F. Stern, Phys. Rev. B 42, 
5166 (1990).
[5] H. Blauvelt, N. Bar-Chaim, D. Fekete, S. Margalit, and 
A. Yariv, Appl. Phys. Lett. 40, 289 (1982).
[6] K.K. Choi, D.C. Tsui, K. Alavi, Appl. Phys. Lett. 50, 
110 (1987).
[7] H.X. Tang, F.G. Monzon, R.H. Blick, M.L. Roukes, M. 
Bichler, and W. Wegscheider, to be published (2000).
[8] T.J. Thornton, M.L. Roukes, A. Scherer, and B.P. Van 
de Gaag, Phys. Rev. Lett. 63, 2128 (1989).
[9] G. Müller, P. Streda, D. Weiss, K. von Klitzing, and G. 
Weimann, Phys. Rev. B 50, 8938 (1994).
[10] T. Fujisawa, T.H. Oosterkamp, W.G. van der Wiel, B.W. 
Broer, R. Aguado, S. Tarucha, and L.P. Kouwenhoven, 
Science 282, 932 (1998).
[11] T. Brandes and B. Kramer, Phys. Rev. Lett. 83, 3021 
(1999).
Fig. 1:
(a) Calculation of the band-structure of the freely sus-
pended two-dimensional electron gas. As indicated the
filled squares mark the non-illuminated trace and the tri-
angles the illuminated one. The Fermi level is pinned at
mid-gap for top and bottom surfaces. The temperature
assumed in the calculations is $T = 10$ K. Top and bot-
tom of the heterostructure are formed by GaAs cap lay-
ers, two AlGaAs:Si donor layers and two AlGaAs spacer
layers around the two-dimensional electron gas.

(b) Scanning electron beam micrograph of the sus-
pended mini-Hall-bar used in the measurements. The
dimensions of this structure are length $\times$ width $= 2 \times 1 \mu\text{m}^2$, while the total thickness of the whole structure is
100 nm.

Fig. 2:
(a) Side-view of the device in Fig. 1(b), demonstrating
the clear undercut; for all samples the same wafer mate-
rial was used.

(b) Aerial view of the suspended single and double
quantum dots. The lithographical diameter of the single
cavity is 800 nm, while the double dots are on the order
of 400 nm. We fabricated several of these samples; data
shown in Fig. 3,4 is obtained from two different cavities A
and B, while the data from the coupled dot is presented
in Fig. 5.

(c) Shown is the longitudinal magnetoresistance $R(B)$
of one of the suspended mini-Hall-bars at $T = 4.2$ K
prior and after illumination as indicated (second sample’s
data not shown). The inset gives a $(1/B)$-plot demon-
strating the periodicity of the oscillations after illumina-
tion (electron density for samples used is obtained as:
$n_s \approx 5.5 \times 10^{15}$ m$^{-2}$).

Fig. 3:
(a) Magnetoresistance trace of the suspended 'open'
quantum dot (cavity A), prior to illumination (note the
large resistance). The leads contain several transport
channels, resulting in a strong coupling, i.e. $G > 2e^2/h$.
In the high field region the classical Shubnikov-de Haas
oscillations appear, while at low fields we find commen-
surability oscillations (circle). The two arrows mark the
onset of the spin splitting. Inset gives a clear $1/B$-
periodicity of the oscillations, we obtain a density of
$n_{s,\text{cav}A} = 5.65 \times 10^{15}$ m$^{-2}$.

(b) Corresponding Shubnikov-de Haas data of cav-
ity B (evaluation of the data in the inset gives $n_{s,\text{cav}B} =
6.38 \times 10^{15}$ m$^{-2}$). For this cavity we find even better
pronounced commensurability oscillations (circle). Inset
depicts the experimental setup for the transport mea-
surements. Also marked by arrows is the occurrence of
the first spin splitting.

Fig. 4:
(a) At the lowest temperatures (4.2 K-plot) we
find commensurability resonances and superimposed $B$
periodic Aharonov-Bohm type oscillations from which we
derive an ‘electronic’ diameter of the cavity of $\sim 450$ nm
for cavity A. The oscillations clearly vanish at 10 K
and under illumination. The geometric resonances are
also modified under illumination. The commensurab-
ility resonances equally allow the determination of the
cavity diameter: Calculating the cyclotron radii we find
$r_c = 652$ nm, $r_d = 680$ nm, $r_c^d = 484$ nm, $r_c^b = 357$ nm,
$r_c^a = 265$ nm (see text for details). Insets give some of
the possible orbits: The upper sketch $\alpha$ shows the ideal
case, while in the lower one $\beta$ we allowed a finite contact
diameter, demonstrating the occurrence of the different
cyclotron radii.

(b) Similar commensurability oscillations and almost
identical fine structure for cavity B. Calculating the radii
of the cyclotron orbits yields: $r_c = 874$ nm, $r_b = 539$ nm,
$r_c^a = 210$ nm. Inset ($\gamma$) sketches a possible electron tra-
jectory with maximum cyclotron radius.

Fig. 5:
Drain/source conductance of the coupled dot in the
tunneling regime for different magnetic fields at 4.2 K.
Marked with $E_0$, $E_1$, and $E_2$ are the different possible
charging states, changing upon increasing the field (see
text for details). Inset indicates sequential electron tun-
neling through the coupled dot.
This figure "prbf1a.jpg" is available in "jpg" format from:

http://arxiv.org/ps/cond-mat/0008326v1
This figure "prbf1b.JPG" is available in "JPG" format from:

http://arxiv.org/ps/cond-mat/0008326v1
This figure "prbf2a.jpg" is available in "jpg" format from:

http://arxiv.org/ps/cond-mat/0008326v1
This figure "prbf2b.JPG" is available in "JPG" format from:

http://arxiv.org/ps/cond-mat/0008326v1
This figure "prbf2c.JPG" is available in "JPG" format from:

http://arxiv.org/ps/cond-mat/0008326v1
This figure "prbf3a.jpg" is available in "jpg" format from:

http://arxiv.org/ps/cond-mat/0008326v1
This figure "prbf3b.JPG" is available in "JPG" format from:

http://arxiv.org/ps/cond-mat/0008326v1
This figure "prbf4a.JPG" is available in "JPG" format from:

http://arxiv.org/ps/cond-mat/0008326v1
This figure "prbf4b.JPG" is available in "JPG" format from:

http://arxiv.org/ps/cond-mat/0008326v1
This figure "prbf5.JPG" is available in "JPG" format from:

http://arxiv.org/ps/cond-mat/0008326v1