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We report on the fabrication and characterization of a device which allows the formation of an antidot lattice (ADL) using only electrostatic gating. The antidot potential and Fermi energy of the system can be tuned independently. Well defined commensurability features in magnetoresistance as well as magnetothermopower are observed. We show that the thermopower can be used to efficiently map out the potential landscape of the ADL. © 2010 American Institute of Physics. [doi:10.1063/1.3493268]

A two-dimensional electron system (2DES) with a regular array of scatterers is referred to as an antidot lattice (ADL). Over the past two decades, such systems have been studied in great detail revealing a variety of intriguing physical phenomena, ranging from classical pinned orbits in magnetic fields (commensurability)[1] to Ahoronov–Bohm type quantum interference effects.[2] Recently, there has been a renewed interest in ADLs, as it has been shown that they can alter the band structure of a system, resulting in modified optical[3] and electrical[4] properties. ADLs are usually fabricated by the physical removal of material (etching) in the desired region, resulting in a fixed potential profile in the underlying 2DES.[1] Less destructive techniques such as local oxidation[5] or electrostatic gating[6] have also been employed in the fabrication of ADLs. However, none of the existing techniques allow for an independent variation in the AD potential (U_{AD}) and the Fermi energy (E_F) of the electron sea between the ADs. The fabrication of such devices with independent tunability of U_{AD} and E_F, would allow for a systematic study of the interplay between these two relevant energy scales. In view of recent proposals for scalable spin-based quantum information processing devices in ADLs,[7,8] this tunability is highly desirable. Furthermore, recent studies in 2D mesoscopic devices in GaAs/AlGaAs heterostructures have revealed the possibility of the existence of spin correlated systems formed due to the existence of intrinsic potential modulations within the 2DES.[9] Such tunable devices provide the possibility of realizing well-ordered artificial spin-lattices with tunable magnetism in a semiconductor environment.

In this letter, we describe the properties of ADLs which are induced solely by electrostatic gating. We perform magnetoresistance (MR) and magnetothermopower (MTP) studies to show that U_{AD} and E_F can be controlled independently. We also show that TP is an extremely sensitive tool to study the potential landscape of the ADL system. Silicon δ-doped GaAs/AlGaAs heterostructures with a 30 nm spacer layer with an as-grown number density of 4×10^{15} m^{-2}, and low temperature mobility of 230 m^2/V s (corresponding to an elastic mean free path $\sim$20 μm) were used in our experiments.

Figure 1(a) shows a schematic of the device structure. Following the definition of a mesa by wet etching, standard electron beam lithography and lift-off techniques were used to obtain a metallic (Ti/Au) perforated gate (PG). The AD diameter (d) and spacing (a) are fixed by the geometry of the perforations. A 150 nm thick layer of cross-linked polymethyl methacrylate serves as a dielectric between the PG and a Ti/Au top gate (TG). Application of suitable negative voltages (V_{tg}) on the TG result in the formation of a perfectly periodic ADL in the 2DES. The sheet density, n_s (or E_F), of the itinerant electrons between the scatterers can be continuously varied by applying voltages (V_{pg}) to the PG. Figure 1(b) shows a scanning electron micrograph of one such PG (similar to the ones used in this experiment) prior to deposition of the TG. We were able to reliably fabricate devices with $d(a)$ ranging from 80 to 300 nm (160–700 nm).
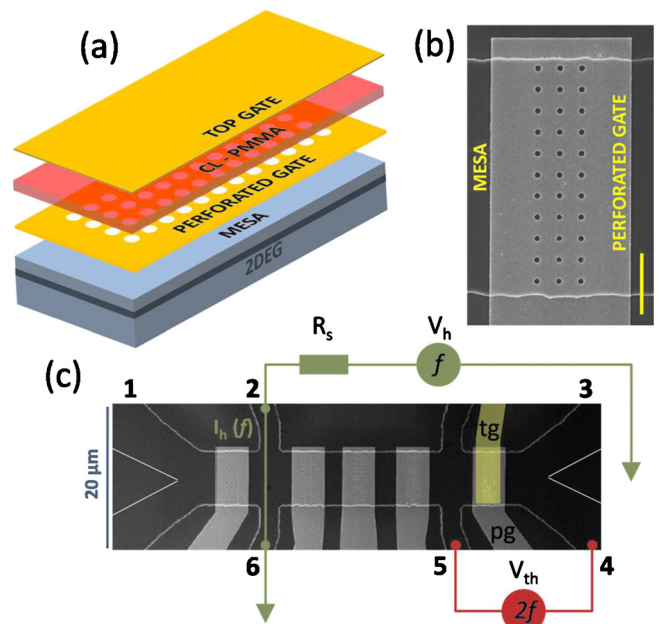
FIG. 1. (Color online) (a) Exploded view of the device structure. (b) Scanning electron micrograph of a device similar to the ones investigated in this work. The scale bar is 2 μm. (c) Schematic of the measurement set-up used to study TP (superimposed on a scanning electron micrograph showing a number of devices on a single chip before the second metallization).

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FIG. 2. (Color online) (a) Schematic of the relevant energy scales in the ADL system: (a1) A situation when U_{AD} just pushes through E_F, (a2) a relatively high U_{AD} resulting in strong scattering centers, (a3) variation in E_F with a fixed U_{AD}. (b) Commensurability in two devices, dev1 (d =300 nm, a=700 nm), and dev2 (d=200 nm, a=400 nm) at 4.2 K. Arrows mark the position 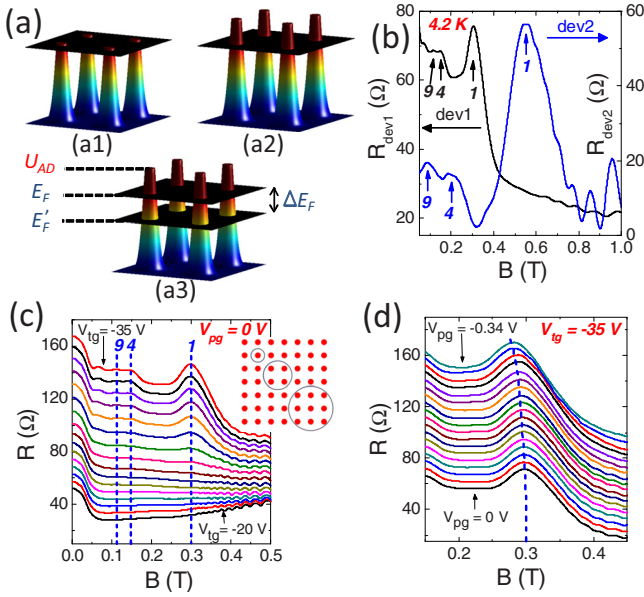of commensurability peaks corresponding to cyclotron orbits around 1, 4, and 9 ADs. (c) MR as V_{tg} is varied from −35 to −20 V. Curves have been offset by 5 Ω for clarity. (d) Variation in the fundamental commensurability peak with V_{pg}, showing a clear modulation of E_F (offset=5 Ω). Dashed vertical lines serve as a guide to the eye.

Measurements were performed in a dilution refrigerator with a base temperature of 30 mK. For resistance measurements a current [I=1 μA, frequency (f)=11.3 Hz] was passed between contacts 1 and 3 [Fig. 1(c)], and the resultant voltage drop across the device (dev1: d=300 nm, a =700 nm) was measured between contacts four and five using a lock-in amplifier yielding the four-probe resistance (R) of the device. Under the influence of a perpendicular magnetic field (B), electrons move in cyclotron orbits and the cyclotron radius (r_c) is given by $r_c = \hbar\sqrt{2\pi n_s}/eB$, where e is the electron charge. At particular values of B, electrons move in pinned orbits around a specific number of ADs resulting in peaks in the resistance whenever r_c is commensurate with the lattice.[1] Figure 2(b) shows commensurability features for two devices (dev1: d=300 nm, a=700 nm; dev2: d=200 nm, a=400 nm) at 4.2 K. V_{tg} was fixed at (−35 V/−50 V) for (dev1/dev2) with V_{pg}=0 V resulting in the formation of a strong periodic AD potential in the 2DES.[10] Clear commensurability peaks are observed in both devices corresponding to pinned orbits around one (fundamental), four, and nine ADs. The higher order peaks (four and nine) shift to lower B for dev2. This shift has been reported previously for ADLs with a high aspect ratio (i.e., d/a) (Ref. 1) and is attributed to chaotic electron dynamics.[11] In contrast, we see no such shift for dev1, which has a smaller aspect ratio. We note that dev1 consists of 33 ADs (in a 3×11 array), which is much lower than typical studies.[1,5] Despite this, we are able to clearly resolve even higher order commensurability features. This may be due to the fact that the nondestructive (gating) technique used to form the ADL does not severely alter the local electron mo-

bility. For the rest of this work we focus on a detailed study of dev1.

Figure 2(c) shows the variation in low temperature (30 mK) MR as a function of V_{tg}. As V_{tg} is reduced (i.e., U_{AD} is increased) from −20 V to −35 V in steps of 1 V (with V_{pg} held at 0 V), we see a clear emergence of commensurability features (for $V_{tg} \lesssim -25$ V), which increase in strength as V_{tg} is reduced. This is illustrated schematically in Fig. 2 (a1 and a2). n_s can be determined from the position of the fundamental commensurability peak (B=0.297 T), and yields a value of n_s=3.96$\times$10^{15} m^{-2}. Alternatively, n_s may be extracted directly from the low-B Shubnikov de-Haas (SdH) oscillations resulting in n_s=3.91$\times$10^{15} m^{-2}, in excellent agreement with that extracted from the commensurability condition. Using this value of n_s we compute r_c corresponding to the B=0.139 T and B=0.110 T and draw the resultant cyclotron orbits [inset of Fig. 2(c)], which confirm that they correspond to orbits around four and nine ADs. We emphasize that the position of the peak is independent of V_{tg} in this range, thus demonstrating that U_{AD} may be continuously varied without any significant effect on E_F of the electron sea. Figure 2(d) shows that at a fixed (V_{tg}=−35 V), E_F can be systematically tuned without affecting U_{AD}. As V_{pg} is varied from 0 V to −0.36 V [illustrated in Fig. 2 (a3)], the position of the peak changes continuously from B=0.297 T to B =0.282 T, without a noticeable change in MR profile. This corresponds to a change in n_s from 3.96$\times$10^{15} to 3.57 $\times$10^{15} m^{-2} (i.e., ΔE_F=1.4 meV). Thus, it is clear that U_{AD} and E_F can indeed be controlled independently in our ADL devices.

We now turn our attention to the TP of the ADL. TP is defined as $S=\lim_{\Delta T \to 0} V_{th}/\Delta T$, where ΔT is the temperature difference across the system, and V_{th} is the resultant thermovoltage. TP often yields vital information about energy flow through the system that cannot be gleaned from standard resistance and conductance measurements.[12,13] Various studies in low-dimensional systems have shown that TP is highly sensitive to the local density of states.[12–14] However there have been extremely limited studies of TP in ADLs.[15,16] We show that TP is an excellent tool to systematically study ADLs. A schematic of the set-up used for TP measurements is shown in Fig. 1(c). A local heating technique is used where a heating current (I_h=10 μA, f=11.3 Hz) flows through one arm of the mesa resulting in a specific ΔT across the device. V_{th} is measured (between contacts four and five) using a lock-in amplifier at $2f$. Note that due to the lack of local temperature sensors, the current device geometry does not allow for an accurate measurement of ΔT and hence S. However, the underlying physics can be explored equally well through a measurement of V_{th}.

Figure 3(a) shows the variation in MTP with V_{tg}. We find that the signature of commensurability in TP is a sharp change in its magnitude. This can be seen clearly when compared with the peak observed in MR [dashed (black) line in Fig. 3(a)]. This is a direct consequence of the Mott formula, appropriately modified for an array of scatterers.[17] The qualitative behavior of TP in our device agrees well with that expected from Ref. 17 (not shown). As expected, the strength of the feature diminishes when V_{tg} changes from −35 to −21 V. Figure 3(b) clearly shows a shift in its position when V_{tg} is held constant and V_{pg} is changed from 0 to −0.34 V. In addition to the ($1/B$)-periodic SdH oscillations, we observe
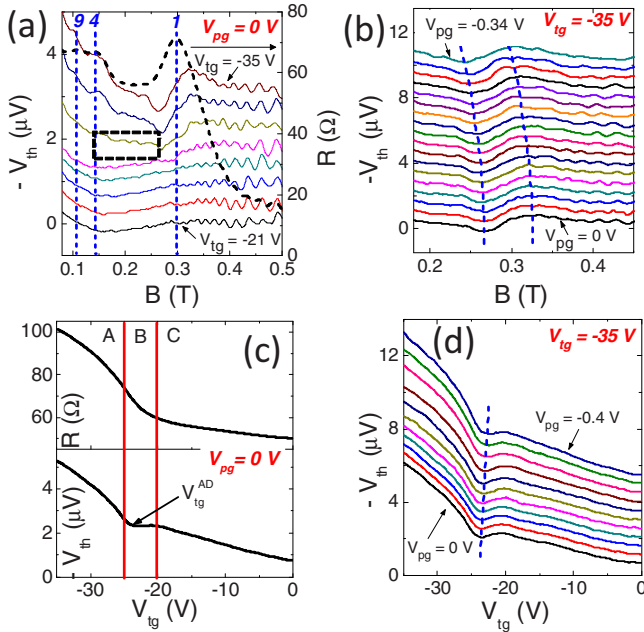
FIG. 3. (Color online) (a) Variation in MTP as V_{tg} is changed from -35 to -21 V ($V_{pg}=0$ V). Dashed line shows the MR at $V_{tg}=-35$ V for comparison. (offset=0.6 μV) (b) A systematic shift in position of the fundamental commensurability feature in MTP. Dashed vertical lines are guides to the eye. (c) (upper/lower) panel shows ($R/-V_{th}$) vs V_{tg}. A, B, and C show three distinct transport regimes in the device. (d) Shift in position of V_{tg}^{AD} with V_{pg} (offset=0.6 μV).

highly reproducible oscillations in TP at low B (<0.3 T), which are periodic in B [boxed region in Fig. 3(a)]. Similar oscillations in MR have been reported earlier and have been associated with quantum interference phenomena in ADLs (Ref. 18) or antidot charging effects in single ADs.[19] Budantsev *et al.*[15] have observed seemingly similar oscillations in the *transverse* TP, and attribute them to interference due to electron orbits *between* four neighboring ADs. However, the observed TP oscillations in our case are associated with electron motion *around* a single AD. A detailed analysis of these oscillations will be the subject of another work. We note that these B-periodic oscillations are clearly absent in MR, reinforcing the fact that TP is a more sensitive tool to probe the electronic structure of ADLs.

We now show that the sensitivity of TP can be exploited to directly investigate the interplay between U_{AD} and E_F. Transport through the ADL can be divided into three regimes (A, B, and C) [Fig. 3(c)]. As V_{tg} is reduced from 0 to ~-20 V (region C), the local number density (in the regions determined by the perforations) gradually changes, resulting in an increase in R (upper panel) and $-V_{th}$ (lower panel). Region B shows a rapid increase in R and a sharp dip in $-V_{th}$. This indicates the onset of strong scattering centers in the 2DES (i.e., the formation of the ADL). In other words, in this region U_{AD} just *pierces* the Fermi surface [illustrated in Fig. 2 (a1)], and electrons see an array of scatterers. This picture is corroborated by the fact that commensurability features in MR (and MTP) only become visible when $V_{tg}<-20$ V. For $V_{tg}<-25$ V (region A), sidewise depletion becomes important, resulting in a further increase in TP due to an increase in U_{AD} [illustrated in Fig. 2 (a2)]. Thus, region B

corresponds to a crossover from a situation when the ADL is not defined to one where $U_{AD}>E_F$. The position of the minimum in $-V_{th}$ (V_{tg}^{AD}) may thus be used to identify region B. In this picture, one would expect that V_{tg}^{AD} should be highly sensitive to E_F. Figure 3(d) shows the variation in $-V_{th}$ with V_{tg} for various V_{pg}. As E_F decreases V_{tg}^{AD} clearly moves to less negative values, indicating that the ADL is induced at lower values of $|V_{tg}|$. The nonmonotonic behavior of TP in region B is a purely electrostatic phenomenon, found to be practically independent of temperature. It may be related to inhomogeneties in U_{AD} resulting from fluctuations in the conduction band due to rapid variations in the impurity potential.[9] However, a more detailed study is required to confirm its origin. Despite this, we can clearly see that the TP is highly sensitive to the relative magnitudes of E_F and U_{AD}, and can be used to accurately determine the region in which the ADL is formed.

In conclusion, we have demonstrated an ADL device where the AD potential and Fermi energy of the system can be controlled independently through electrostatic gating. We have characterized the device using resistance and TP measurements and show that TP is a particularly sensitive tool to study the potential landscape in ADLs.

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