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The low-temperature analysis of narrow GaAs/AlGaAs heterojunction wires

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Abstract. We have measured the magnetoresistance of narrow GaAs/AlGaAs heterojunction wires at temperatures down to 0.04 K and in magnetic fields of up to 1.2 T. The analysis of the low-field magnetoresistance is consistent with a mobility-dependent saturation of the thermal diffusion and phase-breaking lengths. At higher fields, one-dimensional sub-band depopulation and Shubnikov–de Haas oscillations are present. We discuss how studies of the temperature and magnetic field dependence of these various effects provide important information on the possible nature of electronic transport in the wires.

1. Introduction

In recent years, low-temperature magnetoresistance measurements have proven a powerful and versatile tool in the study of small semiconductor devices [1, 2]. In this paper, we describe the use of such techniques in the characterization of very high-mobility heterojunction wires fabricated by a wet etching technique. The high mobilities used in the experiments result in mean free paths larger than the width, so the walls are as effective a source of scattering as any impurities within the wire. At low magnetic fields, where the cyclotron orbit is much larger than the width, universal conductance fluctuations and electron–electron interactions are observed in the magnetoresistance. At higher fields, one-dimensional sub-band depopulation and Shubnikov–de Haas oscillations are also present. We discuss how studies of the temperature and magnetic field dependence of these various effects provide important information on the nature of electronic transport in the wires.

2. *Magnetoresistance effects in narrow wires*

The electron gas in a heterojunction wire is confined to free motion in one direction only and can be considered as quasi-one-dimensional. The density of states consists of one-dimensional sub-bands, the number of which decrease with increasing confinement [3].

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At low temperatures and in the absence of a magnetic field the long-range coherence of the wavefunction results in the well known effects of weak localization [4] and electron–electron interaction (EEI) [5]. These disorder-dependent effects give rise to characteristic magnetoresistance signatures; weak localization is smoothy suppressed by an increasing magnetic field while electron interactions result in a parabolic magnetoresistance [6]

$$\Delta R(B)\alpha - B^2 L_T \tag{1}$$

where

$$L_T = \sqrt{hD/2\pi k_B T} \tag{2}$$

is the thermal diffusion length and D is the diffusion constant. In high-mobility wires, where the mean free path often exceeds the width, boundary scattering results in a suppression of the interactions. A temperature-independent parabolic magnetoresistance associated with the formation of skipping orbits is then observed [7].

The smooth features described above are distorted by the presence of a stochastic interference effect once the phase coherence of the wave function becomes comparable to the wire length [8]. The interference manifests itself as aperiodic structure in the resistance as the magnetic field or carrier density is varied. While the resulting 'magnetofingerprint' is sample specific, the average size and spacing of the conductance fluctuations have been shown to exhibit universal behaviour, independent of the sample size or the degree of disorder. These are the well known universal conductance fluctuations (UCF) [9].

Finally, the magnetic field causes a depopulation of successive one-dimensional subbands, giving rise to an oscillatory magnetoresistance. At higher fields, where the magnetic confinement dominates, the density of states can be considered as two dimensional and the Shubnikov–de Haas (SDH) effect is observed. The characteristic periodicities of the oscillations in these two regimes enables the effective width and carrier density of the wire to de determined [3].

3. Experimental techniques

We have measured the four-terminal magnetoresistance of GaAs/Al_xGa_{1-x}As heterojunction wires ($x = 0.33$) fabricated at the Philips Research Laboratories, Redhill. The heterojunction material was grown by molecular beam epitaxy, the details of which have been described elsewhere [10]. Narrow wire structures were obtained using a wet etching techique in which acidic solutions are used to undercut a photolithographically defined mask [11]. The etch is taken right through the electron gas to the undoped GaAs and results in large sidewall depletion, which can be partially overcome by illumination at low temperatures. The use of high-mobility starting material, in excess of 100 $m^2\,V^{-1}\,s^{-1}$ at 4.2 K, enables low-temperature wire mobilities of up to 60 $m^2\,V^{-1}\,s^{-1}$ to be achieved.

After being glued onto a non-magnetic header, the samples were mounted onto the mixing chamber of a dilution unit. Resistance measurements were made using standard audio-frequency techniques and the temperature was measured with a calibrated ruthenium oxide chip resistor [12]. Great care was taken to ensure good thermal contact and to eliminate RF noise sources from the cryostat. Spurious heating effects were avoided by keeping the voltage across the wires below $k_B T/e$ [13].

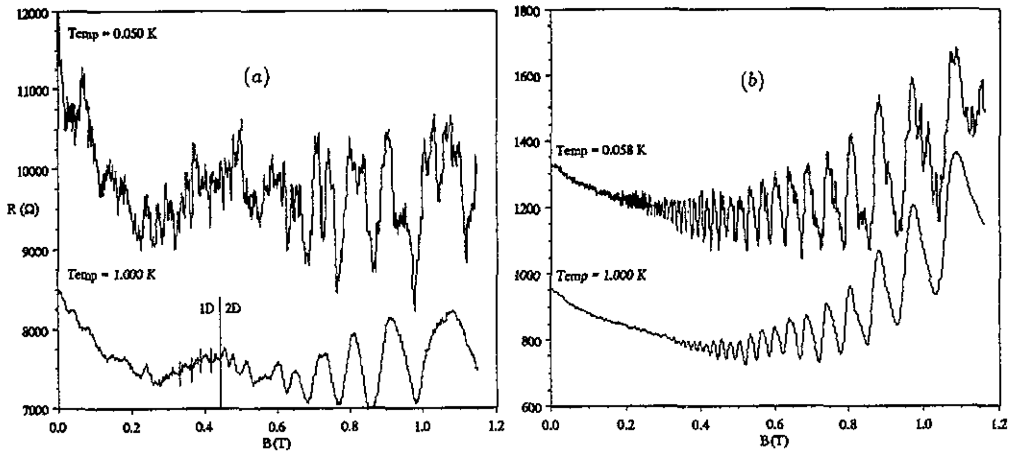

Figure 1. The magnetoresistance of a narrow wire of etched width 1.8 μm measured (*a*) before ($W = 0.55$ μm) and (*b*) after ($W = 1.25$ μm) strong illumination at 4.2 K. For the sake of clarity the low-temperature traces have been shifted by +3 kΩ and +400 Ω in figures 1(*a*) and 1(*b*) respectively.

Table 1. Transport properties measured in a narrow wire at 1 K. The geometrical width of the wire is 1.8 μm and the different conducting widths were obtained by progressive illumination at low temperatures. *Note*: we stress that the values quoted are those measured in the wires and not those obtained from bulk parts of the wafer.

Width (μm)	Carrier density (10^{15} m^{-2})	Mean free path (μm)	Mobility ($m^2 V^{-1} s^{-1}$)	Diffusion constant ($m^2 s^{-1}$)
0.45	1.40	0.33	5.3	0.027
0.55	1.82	0.68	9.6	0.062
0.55	3.73	0.97	9.6	0.128
0.74	3.71	1.31	12.8	0.177
1.25	4.56	3.60	32.3	0.527

4. Results and analysis

The results presented in this paper were obtained on a single wire (etched width 1.8 μm and length 30 μm) in which the effective width and carrier density were altered by illumination from a red LED. In this fashion it was possible to observe a wide variety of transport phenomena in a single sample. We point out, however, that the general features discussed in this paper were also observed in two other wires with etched widths of 1.5 μm and 1.0 μm [13].

In the dark, the conducting width was well below a micrometre and universal conductance fluctuations were clearly observed along with strong one-dimensional subband depopulation (Figure 1(*a*)). Illumination raised the width above a micrometre and the various features of the magnetoresistance became more clearly resolved (figure 1(*b*)). A more detailed analysis of the interaction component was possible and larger numbers of SDH oscillations were observed. The various transport properties produced by successive illumination are summarized in table 1. For conducting widths below a

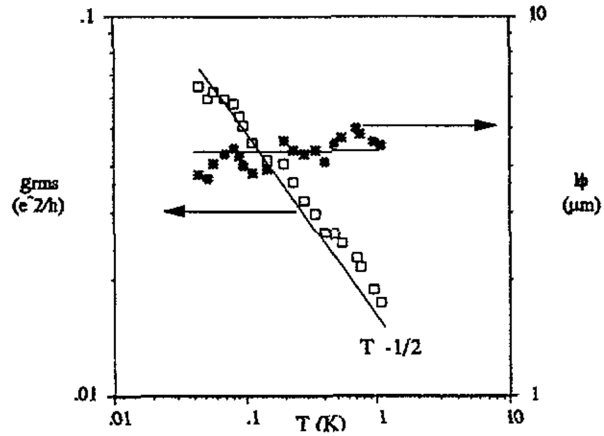

Figure 2. Root mean square amplitude of the UCF (in units of e^2/h), and the corresponding phase-breaking length (in μm). The UCF were analysed over the field range 0–0.15 T.

Table 2. Variation of the phase-breaking length (μm) as a function of mobility. In all cases a temperature-independent $l\phi$ was observed below 1 K.

Width (μm)	Mobility ($m^2 V^{-1} s^{-1}$)	l_ϕ (μm)	Temperature dependence
0.55	9.6	4	Independent
0.74	12.8	6	Independent
1.25	32.3	6	Independent
1.22	48.8	7	Independent

micrometre the effective width was determined from the observation of one-dimensional sub-band depopulation (figure 1(*a*)). For the width value above a micrometre, the reduced lateral confinement meant that depopulation effects were no longer clearly visible [3]. In this case the width was determined using the onset of the EEI, as described by Choi [7] and Taylor [14]. These authors have shown that in high-mobility wires, the skipping orbit effect is suppressed and EEI are observed once the cyclotron orbit becomes comparable to the width.

4.1. *Low-magnetic-field regime: $\omega_c\tau < 1$*

In this section we discuss the features of the magnetoresistance observed at low magnetic fields. These are universal conductance fluctuations superimposed upon a negative background. A detailed discussion of the fluctuations is provided in [15], so here we need only mention their salient features. For the sake of clarity these are summarized in figure 2.

The UCF decay smoothly with increasing temperature and an amplitude analysis in terms of [16] is consistent with a temperature-independent phase-breaking length l_ϕ. Surprisingly, the saturation of l_ϕ occurs at values much shorter than the voltage probe spacing (table 2). Although not expected from theory, this result is in agreement with

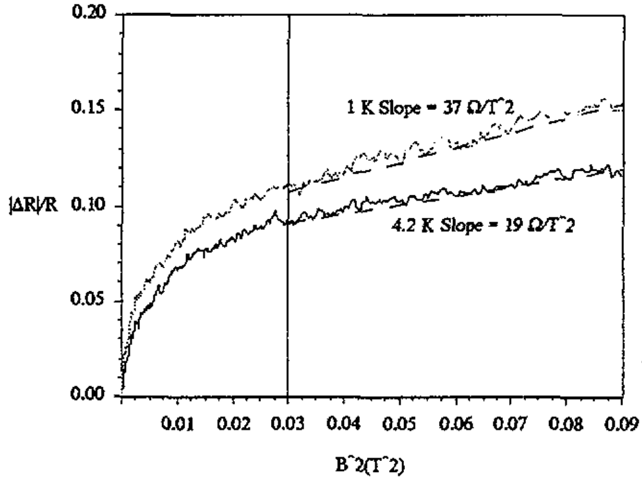

Figure 3. The magnetoresistance of the narrow wire of figure 1(*b*) plotted as a function of B^2 to reveal the temperature-dependent parabolic component associated with electron–electron interactions. $\Delta R = R(B) - R$, where R is the zero-field resistance.

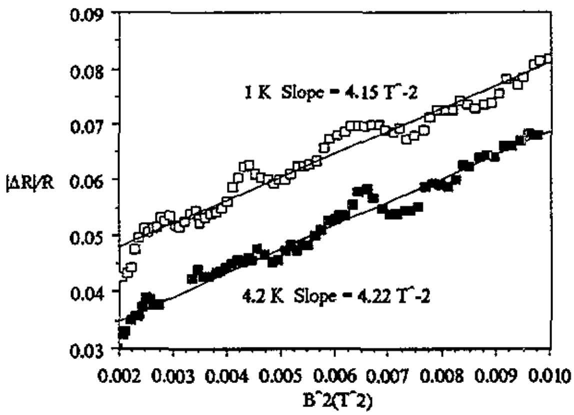

Figure 4. In this diagram we expand the very low-field end of figure 3 to show the temperature-independent parabolic component associated with the formation of skipping orbits.

the observed independence of temperature of the correlation field [15] and with the symmetry of the fluctuations upon field inversion [13] (when $l_\phi < L$, Büttiker [17] has shown that the measured four-terminal resistance is symmetric about $B = 0$).

The background results from a combination of boundary scattering and electron–electron interaction effects. In figure 3 we plot the resistance as a function of the square of magnetic field and see that above 0.175 T the behaviour is consistent with that expected for EEI in a narrow wire (equations (1), (2)). However, at lower magnetic fields the slope of the magnetoresistance is independent of temperature to within 2%, as shown in figure 4. This effect is characteristic of the formation of skipping orbits [7].

In figure 5 we extend our measurements of the low-field background to much lower temperatures and observe an unexpected saturation of the interaction component.

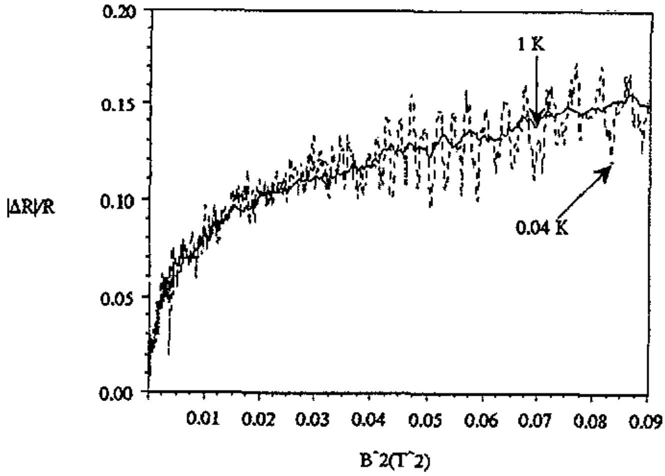

Figure 5. The low-field magnetoresistance of the narrow wire of figure 1(*b*) plotted at two distinct temperatures, to reveal the saturation of the component associated with electron–electron interactions below a degree kelvin.

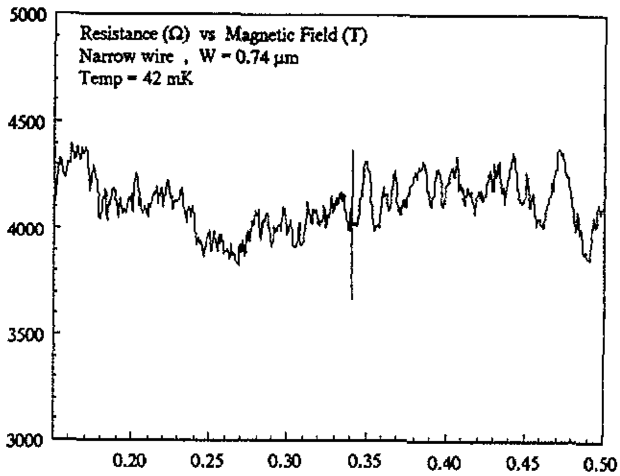

Figure 6. The magnetoresistance of a narrow wire of etched width 1.8 μm and conducting width 0.7 μm plotted at 0.04 K to reveal the existence of a high-frequency cut-off in the magnetoresistance. We point out that the problem of plotting so many points in such a small area means that the cut-off cannot be observed as clearly as on the original chart recorder paper.

Although qualitatively observed in all cases, this behaviour is most readily demonstrated in the higher-mobility wires. Here, the UCF form a proportionally smaller component of the magnetoresistance and so do not obscure the analysis (cf figures 1(*a*) and 1(*b*)). The saturation of the interaction component is characteristic of zero-dimensional behaviour and is normally observed once the thermal length becomes comparable to the length of the wire [7].

$$L = 1.79\,\pi L_T. \tag{3}$$

Our results indicate that the saturation occurs at a temperature of around a kelvin,

Table 3. Comparison of the cyclotron orbit at cut-off to the mean free path l_0 and the width W. Once the orbit becomes smaller than l_0 and W, the electrons move in tight paths between the scattering centres and the walls.

Cut-off field (mT)	Width (μm)	Mean free path (μm)	Cyclotron orbit (μm)
0.36	0.45	0.33	0.35
0.25	0.55	0.68	0.58
0.32	0.55	0.97	0.63
0.35	0.74	1.31	0.59

corresponding to a thermal length between 0.5 μm and 2 μm (see table 1 and equation (2)). Substituting these values into equation (3) we obtain a channel length L between 3 μm and 11 μm, considerably shorter than the physical length of 30 μm. A similar effect has been reported by Choi [7] who suggests the possibility of some diffusion-limiting length scale within the wire.

4.2. High-magnetic-field regime: $\omega_c\tau \geq 1$

We now turn to a discussion of the high-field regime which is reached once the cyclotron orbit becomes smaller than the width. In this limit, the density of states approximates to a series of Landau levels [3] and at high temperatures, smooth SDH oscillations are observed (figure 1). At low temperatures, the magnetoresistance is characterised by the growth of noise-like structure on the oscillations and a sudden cut-off in the low-field UCF. The cut-off is observed as a rapid decay in the high-frequency component of the UCF beyond some characteristic field scale (figure 6).

In table 3 we show that the cut-off occurs once the cyclotron orbit becomes smaller than the mean free path and the width. This corresponds to the high-field limit of the Lee–Stone theory [18] and other authors have previously reported a complete absence of UCF beyond this point [14, 19, 20]. This appears not to be the case in our samples which exhibit noise-like structure well into the oscillatory regime, albeit with an amplitude and spacing different to that observed at lower fields.

A puzzling feature at higher fields is the observation of SDH-like periodicities in the low-temperature structure. As an example of this behaviour, we consider the wire of figure 1(*b*). In figure 7 we plot the SDH oscillations as a function of inverse field and in figure 8 we show the conventional Landau plot obtained from their minima. We also show the plot obtained by treating the larger structure on the oscillations as 'subsidiary' minima. This reveals that much of the subsidiary structure occurs at periodic, rather than random, field values. Although not as clear, similar features can also be discerned on the high-field oscillations of figure 1(*a*). We point out that spin splitting does not seem to be involved since this should occur at the centre of oscillation.

While the above analysis is far from conclusive it at least suggests that caution should be exercised in interpreting the high-field structure in terms of simple UCF; if such an analysis were correct, then we would typically expect the subsidiary structure to exhibit a random field dependence. We therefore suggest that the UCF persist only up to the oscillatory regime, where they are cut off, and that beyond this the additional structure results from some other mechanism. The apparent Landau-like periodicity discussed above indicates that this mechanism might well be related to the density of states.

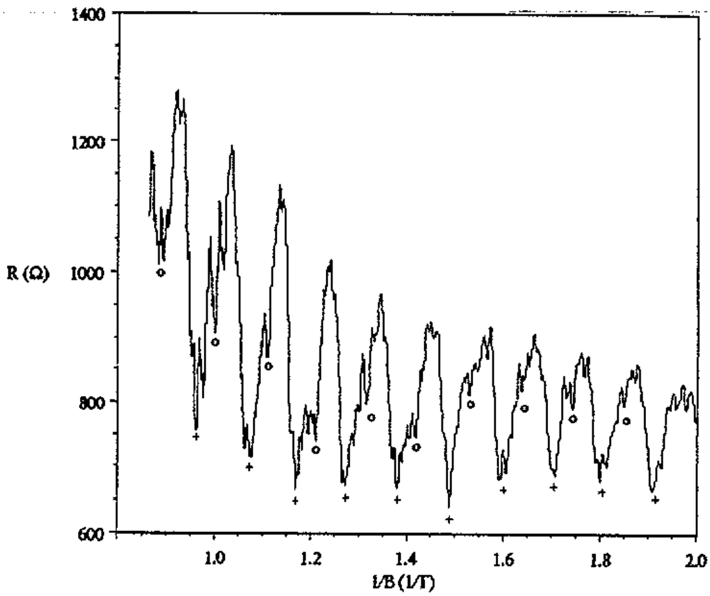

Figure 7. The magnetoresistance of the narrow wire of figure 1(*b*) plotted against inverse field at 0.04 K to reveal the common periodicity of the noise-like structure and the SDH oscillations. Crosses (+) indicate the true SDH minima, identified at higher temperatures, while the circles (O) correspond to the 'subsidiary' minima.

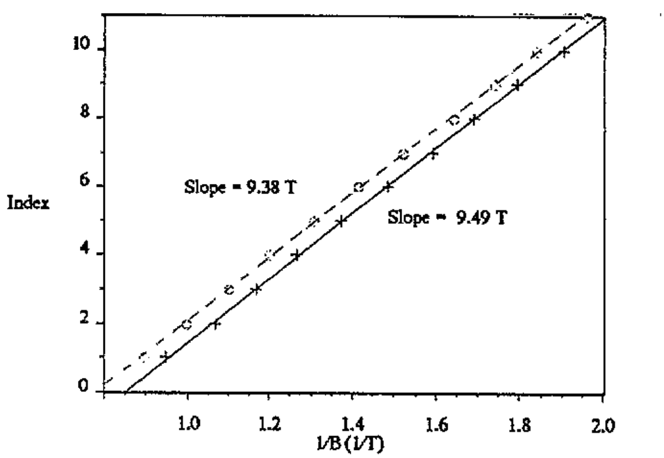

Figure 8. The Landau level plot for the SDH (+) and 'subsidiary' (O) minima of figure 7.

5. Discussion

The saturation of the phase-breaking and thermal diffusion lengths at scales considerably shorter than the channel length is an unexpected result. An earlier publication devoted to an analysis of the UCF [15] suggested that the saturation might result from a breakdown of diffusive motion in our wires. The theory of UCF is derived for metallic systems in which the mean free path is typically much smaller than the phase-breaking length. As a result, the motion is diffusive and the path of the electron can be simplified to a random walk. In our high-mobility samples the long mean free path means that the two length scales may only differ by a numerical factor between one and ten. As a result, the diffusive approximation may no longer be valid.

However, the similar saturation in the thermal diffusion length suggests that the effects we observe might not simply result from theoretical inadequacies. They could result from a size effect characteristic of the device, which sets an upper limit on the spatial extent of the wavefunction. The implication is that even in high-mobility heterojunction wires, macroscopic inhomogeneities exist over a scale of several micrometres. Our results are in qualitative agreement with the earlier work of Choi [7] and our interpretation is supported by the increased phase-breaking length at higher mobilities (table 2). At present we are unable to determine whether such inhomogeneity results directly from the side walls, or whether it is characteristic of the material and is only revealed when the electronic motion is confined quasi-one-dimensionally. We would point out, though, that the observation of skipping orbits is characteristic of smoothly etched walls [21].

The origin of the subsidiary structure in the oscillatory regime remains unresolved. Similar features observed in the dissipationless regime of the quantum Hall effect [22] have recently been explained in terms of a resonant tunnelling between edge states [23]. However, this is not expected to give rise to the periodicities we have observed and, anyway, the relatively low magnetic fields used in our experiments meant that resonant tunnelling was unlikely to occur. We have already discussed the possible role of inhomogeneity in connection with the low-field magnetoresistance, which leads us to suspect its effects at higher fields. The beating of the SDH amplitudes, observed in figure 1, is certainly similar to that previously reported in inhomogeneous semiconductors [24]. In addition, our observation that the oscillations become smoother on increased illumination could be due to the raising of the Fermi level above the long-range potential fluctuations [25]. Extending these arguments to formulate a more quantitative description is difficult, however.

Finally, we point out that the positive component of the magnetoresistance, observed in the oscillatory regime, is consistent with the presence of a parallel conducting path in the highly doped AlGaAs [10]. This provides a temperature-independent component to the conduction at low temperatures and should not affect the validity of the previous arguments.

6. Conclusions

The low-field magnetoresistance of our narrow GaAs/AlGaAs heterojunction wires provides possible evidence for a mobility-dependent length scale, of order several micrometres, which limits the extent of quantum diffusion processes. The origin of this internal length remains unresolved but we speculate that it might provide an indication of the homogeneity along the wire.

At higher fields, a sudden cut-off is observed in the UCF once the cyclotron orbit becomes smaller than the mean free path and the width. Shubnikov–de Haas oscillations are observed and as the temperature is lowered these become distorted by the appearance of additional structure. While the origin of this structure remains unresolved, its apparent $1/B$ periodicity suggests the involvement of a density of states mechanism.

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