Laser controlled molecular switches and transistors

Jörg Lehmann, Sébastien Camallet, Sigmund Kohler, and Peter Hänggi *

Institut für Physik, Universität Augsburg, Universitätsstraße 1, D-86135 Augsburg, Germany

Abstract

We investigate the possibility of optical current control through single molecules which are weakly coupled to leads. A master equation approach for the transport through a molecule is combined with a Floquet theory for the time-dependent molecule. This yields an efficient numerical approach to the evaluation of the current through time-dependent nano-structures in the presence of a finite external voltage. We propose tunable optical current switching in two- and three-terminal molecular electronic devices driven by properly adjusted laser fields, i.e. a novel class of molecular transistors.

Key words: molecular electronics, quantum control
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1 Introduction

Spurred by the ongoing experimental progress in the field of molecular electronics [1–5], the theoretical interest in transport properties of molecules has revived [6]. Tight-binding models for the wire have been used to compute current-voltage characteristics, within a scattering approach [7] and from electron transfer theory [6]. Both approaches bear the same essentials [8]. For high temperatures, the wire electrons loose their quantum coherence and the transport is dominated by incoherent hopping between neighbouring sites [9]. Recently, the current-voltage characteristics has been obtained from a quantum-
chemical \textit{ab initio} description of the molecule [10]. The results were in good agreement with recent experiments [5].

Typical electronic excitation energies in molecules are in the range up to an eV and, thus, correspond to light quanta from the optical and the infrared spectral regime where most of today’s lasers work. It is therefore natural to use such coherent light sources to excite molecules and to study their influence on the transport properties aiming to find a way of manipulating currents. One particularly prominent example of quantum control is the so-called coherent destruction of tunnelling (CDT), \textit{i.e.} the suppression of the tunnelling dynamics in an \textit{isolated} bistable potential by the purely coherent influence of an oscillating bias [11–15]. The crucial point there is that the long-time dynamics in a periodically driven quantum system is no longer dominated by the energies, but rather by the so-called quasienergies [15–17]. The latter may be degenerate for properly chosen driving parameters yielding a divergent time-scale. Inspired by these results, we address in this Letter the question of controlling by use of properly tailored laser fields the transport through time-dependent \textit{open} systems, \textit{i.e.} systems that allow for a particle exchange with external leads.

For the computation of electrical currents through wires exposed to strong laser fields, we put forward Floquet approach [18]. The central idea of this method lies in a non-perturbative solution of the Schrödinger equation of the isolated time-dependent wire plus laser field, while the wire-lead coupling is treated perturbatively. The resulting density operator equation is decomposed into a time-dependent Floquet basis permitting a numerically efficient treatment. We generalise here this method to the analysis of networks with an arbitrary number of contacts to leads. Subsequently we apply the so-obtained formalism to the investigation of optical current switching in two- and three-terminal devices as prototypical examples of a new class of molecular transistors.

2 Model for wire and leads

We embark by specifying the model Hamiltonian of the entire system as sketched in Fig. 1. It consists of the molecule in the laser field, ideal leads, and the molecule-leads coupling Hamiltonian,

\[ H(t) = H_{\text{molecule}}(t) + H_{\text{leads}} + H_{\text{molecule-leads}}. \]  

(1)

The irradiated molecule is modelled by a tight-binding description taking into account \( N \) molecular orbitals \(|n\rangle\), which are relevant for the transport. Disregarding the electron-electron interaction, the most general form of the Hamil-
Fig. 1. Molecular circuit consisting of $N = 6$ sites of which the sites $1, \ldots, L$ are coupled to $L = 4$ leads.

The Hamiltonian reads

$$H_{\text{molecule}}(t) = \sum_{n,n'} H_{nn'}(t) c_n^\dagger c_{n'},$$

where the fermionic operators $c_n$ and $c_n^\dagger$ destroy and create, respectively, an electron in the molecular orbital $|n\rangle$. The sums extend over all tight-binding orbitals. The $\mathcal{T}$-periodic time-dependence of the single-particle Hamiltonian $H_{nn'}(t) = H_{nn'}(t + \mathcal{T})$, reflects the influence of the laser field with frequency $\Omega = 2\pi/\mathcal{T}$. The $L$ ideal leads are described by grand-canonical ensembles of electrons at temperature $T$ and electro-chemical potential $\mu_\ell, \ell = 1, \ldots, L$. Thus, the lead Hamiltonian reads $H_{\text{leads}} = \sum_{q\ell} \epsilon_{q\ell} c_{q\ell}^\dagger c_{q\ell}$, where $c_{q\ell}$ destroys an electron in state $q$ in lead $\ell$. All expectation values of lead operators can be traced back to $\langle c_{q\ell}^\dagger c_{q'\ell'} \rangle = \delta_{qq'} \delta_{\ell\ell'} f(\epsilon_{q\ell} - \mu_\ell)$, where $f(\epsilon) = (1 + e^{\epsilon/k_B T})^{-1}$ denotes the Fermi function. The model is completed by the molecule-leads tunnelling Hamiltonian

$$H_{\text{molecule-leads}} = \sum_{q\ell} V_{q\ell} c_{q\ell}^\dagger c_{\ell} + \text{h.c.},$$

that connects each lead directly to one of the suitably labelled molecular orbitals. Since we are not interested here in the effects that arise from the microscopic details of the molecule-lead coupling, we restrict our analysis in the following to energy-independent couplings, i.e. $\Gamma_\ell = (2\pi/\hbar) \sum_q |V_{q\ell}|^2 \delta(\epsilon - \epsilon_{q\ell})$. 

3
3 Perturbative description and Floquet ansatz

Let us assume that the dynamics of the driven wire is dominated by the time-dependent wire Hamiltonian so that the coupling to the leads can be taken into account as a perturbation. This allows to derive by use of standard methods the approximate equation of motion for the total density operator \( \dot{\rho}(t) \),

\[
\dot{\rho}(t) = -\frac{i}{\hbar} [H_{\text{molecule}}(t) + H_{\text{leads}}, \rho(t)] \quad \text{(4)}
\]

\[-\frac{1}{\hbar^2} \int_0^\infty d\tau [H_{\text{molecule}} - \text{leads}, \tilde{H}_{\text{molecule}} - \text{leads}(t - \tau, t), \rho(t)]].
\]

We have omitted a transient term that depends purely on the initial preparation. The tilde denotes operators in the interaction picture with respect to the molecule plus the lead Hamiltonian, \( \tilde{O}(t, t') = U_\uparrow(t, t')O(t)U_\downarrow(t, t') \), where \( U_\uparrow(t, t') \) is the time-evolution operator without the coupling. The first term describes the coherent dynamics of the electrons on the wire, while the second term represents incoherent hopping of electrons between the leads and the wire.

The net (incoming minus outgoing) electrical current that flows from lead \( \ell \) into the molecule is then given by the rate at which the electron number in the corresponding lead decreases multiplied by the electron charge \(-e\),

\[
I_\ell(t) = e \frac{d}{dt} \langle N_\ell \rangle .
\]

Note that this expectation value is time-dependent through the non-equilibrium density operator \( \rho(t) \). To evaluate the right-hand side of Eq. (5), we employ Eq. (4) to derive after some algebra the result

\[
I_\ell(t) = -e \Gamma_\ell \left\{ \text{Re} \int_0^\infty \frac{d\tau}{\hbar} \int \frac{d\epsilon}{\pi} e^{i\epsilon\tau/\hbar} f(\epsilon - \mu_\ell) \left[ c_\ell^\dagger(t - \tau, \epsilon) + \langle c_\ell^\dagger(t - \tau, t) \rangle \right] \right\}.
\]

This expression still contains the yet unknown expectation values of solely those wire operators with a direct connection to lead \( \ell \). It depends in particular on the Heisenberg operators \( c_\ell^\dagger(t - \tau, t) \) and thus implicitly on the dynamics of the driven wire. Let us therefore focus on the single-particle dynamics of the periodically time-dependent wire Hamiltonian \( H_{\text{wire}}(t) \). An established procedure for the solution of the corresponding Schrödinger equation is to employ a Floquet ansatz amounting to a non-perturbative treatment of the external driving. There one uses the fact that a complete set of solutions is of the form \( |\Psi_\alpha(t)\rangle = \exp(-i\epsilon_\alpha t/\hbar) |\Phi_\alpha(t)\rangle \). The so-called quasienergy-
gies $\epsilon_\alpha$ take over the role of the energy eigenvalues in static systems and govern the long-time dynamics. The Floquet modes $|\Phi_\alpha(t)\rangle$ obey the time-periodicity of the driving field which allows to express them as a Fourier series, $|\Phi_\alpha(t)\rangle = \sum_{k=-\infty}^{\infty} \exp(-ik\Omega t)|\Phi_{\alpha,k}\rangle$. They can be obtained from the eigenvalue equation \[16,17,15\]

\[
\left( \sum_{n,n'} |n\rangle H_{nn'}(t)\langle n'| - i\hbar \frac{d}{dt} \right) |\Phi_\alpha(t)\rangle = \epsilon_\alpha |\Phi_\alpha(t)\rangle .
\]

Moreover, the Floquet modes define the complete set of operators

\[
c_\alpha(t) = \sum_n \langle \Phi_\alpha(t) | n \rangle c_n,
\]

whose time-evolution assumes the convenient form $\tilde{c}_\alpha(t-\tau, t) = \exp(i\epsilon_\alpha \tau / \hbar)c_\alpha(t)$. The orthogonality of the Floquet states at equal times \[16,17,15\] yields the back-transformation $c_n = \sum_\alpha \langle n | \Phi_\alpha(t) \rangle$ and thus results in the required spectral decomposition. Using (8) and performing the energy and the $\tau$-integration in Eq. (6), we obtain for the time-averaged current the main result

\[
\bar{I}_\ell = -\frac{e\Gamma_\ell}{\hbar} \sum_{\alpha k} \left[ \langle \Phi_{\alpha,k} | \ell \rangle \langle \ell | \Phi_{\alpha,k} \rangle f(\epsilon_\alpha + k\hbar\Omega - \mu_\ell) \\
- \sum_{\beta k'} \langle \Phi_{\alpha,k'+k} | \ell \rangle \langle \ell | \Phi_{\beta,k'} \rangle R_{\alpha\beta,k'} \right].
\]

Here, we have introduced the expectation values $R_{\alpha\beta}(t) = \langle c_\alpha^\dagger(t) c_\beta(t) \rangle$, which assume in the long-time limit the time-periodicity of the driven system and thus can be decomposed into the Fourier series $R_{\alpha\beta}(t) = \sum_k \exp(-ik\Omega t)R_{\alpha\beta,k}$. It is straightforward to derive for the $R_{\alpha\beta,k}$ from the density operator equation (4) the following set of inhomogeneous linear equations

\[
\frac{i}{\hbar}(\epsilon_\alpha - \epsilon_\beta + k\hbar\Omega)R_{\alpha\beta,k} \\
= \frac{1}{2} \sum_{\ell k'} \Gamma_\ell \left\{ \sum_{\beta k''} \langle \Phi_{\beta,k''+k'} | \ell \rangle \langle \ell | \Phi_{\beta,k''+k} \rangle R_{\alpha\beta,k'} \\
+ \sum_{\alpha' k''} \langle \Phi_{\alpha',k''+k'} | \ell \rangle \langle \ell | \Phi_{\alpha',k''+k} \rangle R_{\alpha'\beta,k'} \\
- \langle \Phi_{\beta,k'-k} | \ell \rangle \langle \ell | \Phi_{\alpha,k'} \rangle f(\epsilon_\alpha + k'\Omega - \mu_\ell) \\
- \langle \Phi_{\beta,k'} | \ell \rangle \langle \ell | \Phi_{\alpha,k'+k} \rangle f(\epsilon_\beta + k'\Omega - \mu_\ell) \right\},
\]

which will be solved numerically. We have found that even in the case of strong driving where the Floquet states comprise many sidebands, a few Fourier coefficients $R_{\alpha\beta,k}$ are in fact sufficient to obtain numerical convergence. This justifies \textit{a posteriori} the use of the Floquet states as a basis set.

To conclude the technical part of this work, we note that our approach goes
beyond a linear response treatment of the driving and additionally does not use a so-called rotating wave approximation (RWA) [19,20], which neglects the oscillatory contributions to $R_{\alpha\beta}(t)$ by the ansatz $R_{\alpha\beta,k} = P_\alpha \delta_{\alpha,\beta} \delta_{k,0}$. In fact, we found that a RWA solution delivers inaccurate results in the vicinity of quasienergy degeneracies.

4 Optical current gate

As a first setup that may be suitable as a current control device, we investigate the transport through a two-level system, i.e. a wire that consists of $N = 2$ sites — one of them is coupled to the left lead and the other to the right lead. Then the time-dependent wire Hamiltonian reads in the basis of the molecular orbitals

$$H_{\text{molecule}}(t) = \begin{pmatrix} E_L & -\Delta \\ -\Delta & E_R \end{pmatrix} + A \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \cos(\Omega t),$$

(11)

where $\Delta$ denotes the tunnel matrix element between the two sites and $E_L$ and $E_R$ are the corresponding on-site energies. The laser field contributes to the Hamiltonian (11) a time-dependent bias with amplitude $A = -eE_0d$, i.e. charge times electrical field strength times the site-to-site distance. Note that the electrical field may be drastically enhanced due to the presence of the metallic tips [21]. The effective coupling to each lead is assumed to be equal, $\Gamma_\ell = \Gamma$, and an external voltage $V$ is taken into account by a difference in the electro-chemical potentials, $\mu_L - \mu_R = -eV$.

We use in all numerical calculations the tunnel matrix element $\Delta$ as the energy unit and assume that the effective couplings to the leads are by one order of magnitude smaller, $\hbar \Gamma = 0.1\Delta$. This corresponds to a large contact resistance and ensures the applicability of a perturbational approach. A realistic value is $\Delta = 0.1eV$, resulting in a current unit $e\Gamma = 0.256\mu A$. For a site-to-site distance of $10\AA$ and a laser frequency $\Omega = 10\Delta/\hbar$, the driving amplitudes considered below correspond to an electrical field amplitude of $10^6 V/cm$ at $1 \mu m$ wavelength.

The time-averaged current $\bar{I} = \bar{I}_L = -\bar{I}_R$ through the molecule in a case where both on-site energies are equal is depicted in Fig. 2. As a striking feature, we find that at certain values of the driving amplitude, the current collapses to less than 1% of its maximal value reached in the absence of the driving. Closer inspection (not shown) reveals that the width of this depression is proportional to the molecule-lead coupling $\Gamma$. Comparison with the quasienergy spectrum in the lower panel demonstrates that the current break downs occur at quasienergy crossings. This relates the present phenomenon to...
Fig. 2. Average current and quasienergy spectrum versus driving amplitude for a wire which consists of two sites between two electrodes (cf. inset) for unbiased ($E_R = E_L = 0$, solid lines) and biased ($E_R = -E_L = 0.1\Delta$, dashed lines) on-site energies. The leads’ chemical potentials are $\mu_R = -\mu_L = 10\Delta$; the other parameters read $\hbar\Omega = 10\Delta$, $k_B T = 0.25\Delta$, $\hbar\Gamma = 0.1\Delta$.

the CDT, i.e. the standstill of the tunnel dynamics in a driven bistable potential at quasienergy crossings [11]. For the isolated two-level system (11) with $\Delta \ll \Omega, A$, the CDT condition reads $J_0(2A/\hbar\Omega) = 0$ [12], i.e. the suppression of the tunnelling dynamics is related to the zeros of the Bessel function $J_0$. As our analysis reveals, the same condition results in a suppression of the transport through the open system.

An external voltage may be of peculiar influence to the on-site energies of a molecular wire [22] and cause an effective bias $E_L \neq E_R$ in originally symmetric molecules. Thus, a crucial question is whether the above current suppression is stable against such a modification. The broken lines in Fig. 2 demonstrate that this is indeed the case. Although the quasienergies now form an avoided crossing, the current breakdows do survive; they are even more pronounced, but slightly shifted towards larger driving amplitudes. This robustness of CDT based current control combined with the huge on/off ratio suggests the presented setup as a promising alternative to structural chemistry-based switching devices [23,24].
Fig. 3. Average currents through contacts $C_1$ (solid) and $C_2$ (broken) as a function of the polarisation angle $\phi$ for the three-terminal device depicted in the inset. The chemical potentials are $\mu_E = -\mu_{C_1} = -\mu_{C_2} = 50\Delta$; the on-site energies $E_n = 0$. The driving field is specified by the strength $A = 25\Delta$ and the angular frequency $\Omega = 10\Delta/\hbar$; the effective coupling is $\hbar\Gamma = 0.1\Delta$ and the temperature $k_BT = 0.25\Delta$. The maximal value of the current ratio $I_{C_1}/I_{C_2} \approx 100$ is assumed at $\phi = 60^\circ$.

5 Optical current router

An experimentally more ambitious configuration consists in a planar molecule with $N = 4$ sites, three of which are coupled to a central site and are directly connected to leads (cf. inset of Fig. 3). We borrow from electrical engineering the designation $E$, $C_1$, and $C_2$. Here, an external voltage is always applied such that $C_1$ and $C_2$ have equal electro-chemical potential, i.e. $\mu_{C_1} = \mu_{C_2} \neq \mu_E$. In a perfectly symmetric molecule, where all on-site energies equal each other, reflection symmetry at the horizontal axis ensures that any current which enters at $E$, is equally distributed among $C_1, C_2$, thus $I_{C_1} = I_{C_2} = -I_E/2$. Since this structure in Fig. 3 is essentially two-dimensional, we have to take also the polarisation of the laser field into account. We assume it to be linear with an polarisation angle $\phi$ as sketched in the inset of Fig. 3. The effective driving amplitudes of the orbitals which are attached to the leads acquire now a geometric factor which is only the same for both orbitals $C_1$ and $C_2$ when $\phi = 0$. For any other polarisation angle, the mentioned symmetry is broken and the outgoing currents may be different from each other. The difference may be huge, as depicted in Fig. 3. Their ratio varies from unity for $\phi = 0$ up to the order of 100 for $\phi = 60^\circ$. Thus, adapting the polarisation angle enables one to route the current towards the one or the other drain.

Alternatively, one can keep the polarisation angle at $\phi = 0$ and break the reflection symmetry by using an intrinsically asymmetric molecule, as sketched in the inset of Fig. 4. This allows to control sensitively the ratio of the outgoing currents by the strength $A$ of the external field, cf. Fig. 4. The switching range comprises up to four orders of magnitude with an exponential sensitivity.
Fig. 4. Ratio of the outgoing average currents versus driving strength $A$ for the three-terminal device at a polarisation angle $\phi = 0$. The filled circle in the inset depicts a site with an on-site energy $E_{C_1}$ that differs from the others. All other on-site energies and parameters as in Fig. 3.

6 Concluding remarks

We have presented a method for the efficient numerical computation of currents through periodically time-dependent networks with two or more contacts to external leads. The application to two types of setups substantiated that external fields bear a wealth of possibilities for the manipulation of electrical currents: in a molecular wire the current can be suppressed by proper time-dependent fields. In a three terminal device, it is possible to route by tailored optical fields the current that enters from a source towards the one or the other drain.

The authors hope that their proposals will motivate experimentalists to accept the challenge of implementing the proposed molecular wire schemes in the laboratory. The two-terminal current gate can possibly be realized using break junctions exposed to a laser field. Alternatively, one could use a self-assembled, laser-irradiated maze-like layer of sparsely distributed conducting molecules on a conducting surface. Then by positioning a scanning tunnelling microscope tip directly over one such molecule, it should be possible to measure the features of the predicted gating behaviour. Experimentally more ambitious is the realization of the arrangement in Fig. 3 with a planar molecule contacted to three electrodes. Here again, laser-irradiated self-assemblies of molecules such as carbon nanotube complexes or of biomolecules like metalised DNA [25], or the use of cationic lipid-DNA complexes [26] as DNA-nanocables, with the centre-molecule covalently bound to such planar structures, might make the experiment feasible.

A completely different realization of our findings should be possible in semi-
conductor heterostructures. There, instead of a molecule, coherently coupled quantum dots [27] form the central system. Furthermore, owing to the lower level spacings, the suitable frequency of the coherent radiation source is then in the microwave spectral range.

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References

[1] M. A. Reed, C. Zhou, C. J. Muller, T. P. Burgin, J. M. Tour, Conductance of a molecular junction, Science 278 (1997) 252.

[2] X. D. Cui, A. Primak, X. Zarate, J. Tomfohr, O. F. Sankey, A. L. Moore, T. A. Moore, D. Gust, G. Harris, S. M. Lindsay, Reproducible measurement of single-molecule conductivity, Science 294 (2001) 571.

[3] C. Joachim, J. K. Gimzewski, A. Aviram, Electronics using hybrid-molecular and monolayer devices, Nature 408 (2000) 541.

[4] J. H. Schön, H. Meng, Z. Bao, Self-assembled monolayer organic field-effect transistors, Nature 413 (2001) 713.

[5] J. Reichert, R. Ochs, D. Beckmann, H. Weber, M. Mayor, H. v. Loehneysen, Driving current through single organic molecules, Phys. Rev. Lett. 88 (2002) 176804.

[6] A. Nitzan, Electron transmission through molecules and molecular interfaces, Ann. Rev. Phys. Chem. 52 (2001) 681.

[7] V. Mujica, M. Kemp, M. A. Ratner, Electron conduction in molecular wires. i. a scattering formalism, J. Chem. Phys. 101 (1994) 6849.

[8] A. Nitzan, A relationship between electron-transfer rates and molecular conduction, J. Phys. Chem. A 105 (2001) 2677.

[9] E. G. Petrov, P. Hänggi, Nonlinear electron current through a short molecular wire, Phys. Rev. Lett. 86 (2001) 2862.

[10] J. Heurich, J. C. Cuevas, W. Wenzel, G. Schön, Electrical transport through single-molecule junctions: from molecular orbitals to conduction channels, cond-mat/ (2001) 0110147.
[11] F. Grossmann, T. Dittrich, P. Jung, P. Hänggi, Coherent destruction of tunneling, Phys. Rev. Lett. 67 (1991) 516.

[12] F. Großmann, P. Hänggi, Localization in a driven two-level dynamics, Europhys. Lett. 18 (1992) 571.

[13] M. Morillo, R. I. Cukier, Control of proton transfer reactions with external fields, J. Chem. Phys. 98 (1993) 4548.

[14] I. A. Goychuk, E. G. Petrov, V. May, Control of the dynamics of a dissipative two-level system by a strong periodic field, Chem. Phys. Lett. 253 (1996) 428.

[15] M. Grifoni, P. Hänggi, Driven quantum tunneling, Phys. Rep. 304 (1998) 229.

[16] J. H. Shirley, Solution of the Schrödinger equation with a Hamiltonian periodic in time, Phys. Rev. 138 (1965) B979.

[17] H. Sambe, Steady states and quasienergies of a quantum-mechanical system in an oscillating field, Phys. Rev. A 7 (1973) 2203.

[18] J. Lehmann, S. Kohler, P. Hänggi, A. Nitzan, Molecular wires acting as quantum ratchets, Phys. Rev. Lett. 88 (2002) 228305.

[19] R. Blümel, A. Buchleitner, R. Graham, L. Sirko, U. Smilansky, H. Walter, Dynamical localisation in the microwave interaction of Rydberg atoms: The influence of noise, Phys. Rev. A 44 (1991) 4521.

[20] C. Bruder, H. Schoeller, Charging effects in ultrasmall quantum dots in the presence of time-varying fields, Phys. Rev. Lett. 72 (1994) 1076.

[21] F. Demming, J. Jersch, K. Dickmann, P. I. Geshev, Calculation of the field enhancement on laser-illuminated scanning probe tips by the boundary element method, Appl. Phys. B 66 (1998) 593.

[22] V. Mujica, A. E. Roitberg, M. Ratner, Molecular wire conductance: Electrostatic potential spatial profile, J. Chem. Phys. 112 (2000) 6834.

[23] J. Chen, M. A. Reed, A. M. Rawlett, J. M. Tour, Large on-off ratios and negative differential resistance in a molecular electronic device, Science 286 (1999) 1550.

[24] C. P. Collier, G. Mattersteig, E. W. Wong, Y. Luo, K. Beverly, J. Sampaio, F. M. Raymo, J. F. Stoddart, J. R. Heath, A [2]catenane-based solid state electronically reconfigurable switch, Science 289 (2000) 1172.

[25] E. Braun, Y. Eichen, U. Sivan, G. Ben-Yoseph, DNA-templated assembly and electrode attachment of a conducting silver wire, Nature 391 (1998) 775.

[26] O. J. Rädler, I. Koltover, A. Jamieson, T. Salditt, C. R. Safinya, Structure and interfacial aspects of self-assembled cationic lipid-DNA gene carrier complexes, Langmuir 14 (1998) 4272.

[27] R. H. Blick, R. J. Haug, J. Weis, D. Pfannkuche, K. v. Klitzing, K. Eberl, Single-electron tunneling through a double quantum dot: The artificial molecule, Phys. Rev. B 53 (1996) 7899.