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In anticipation of the continued size reduction of switching elements to the molecular level, new approaches to materials, memory, and switching elements have been developed. Two of the three most promising switching phenomena include electron tunneling in short periodic arrays and soliton switching in conjugated systems. Assuming a three-dimensional architecture, the element density can range from $10^{13}$ to $10^{18}$ per cc. In order to make the fabrication of such a molecular electronic device computer feasible, techniques for accomplishing lithography at the molecular scale must be devised. Three approaches possibly involving biological and Langmuir–Blodgett materials are described.

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I. INTRODUCTION

If one extrapolates gains in transistor size reduction into the future, then it is readily anticipated that electronic switches will be at the molecular size level, i.e., 20–200 Å in 20–30 years. At this point it is appropriate to consider materials whose molecular structure is conducive to switching or multistate phenomena rather than silicon whose structure is isotropic. The point of view adapted here is that of building structures up from the molecular level rather than imposing structure from the outside. Ultimately to succeed in either case we must become aware of the chemical or bonding forces at the molecular level. Not only must we be aware of them, but we must recognize them as being among the sharpest of tools.

While molecular level fabrication techniques are a clear necessity for the development of processors and sensors based on Molecular Electronic Devices (MEDs), it is a primary object of this discussion to suggest their importance in possible future developments in semiconductor lithographic techniques. Another object of this paper is to review briefly recent developments given at the 2nd International Workshop on Molecular Electronic Devices, abbreviated WMED2 herein, and call particular attention to new concepts applicable to molecular fabrication. Other conceptual aspects of molecular electronic devices not discussed here include soliton generators, soliton reversers, molecular memory elements, smart molecules, soliton light emitters, and molecular micro lasers.

II. MED FABRICATION VIA MODULAR CHEMISTRY

While modern synthetic chemists have demonstrated a remarkable ability to prepare virtually any compound imagined, it has been recognized that the preparation of molecular electronic devices via traditional bulk methods is unlikely to be a useful or an efficient approach. Accordingly, it was

FIG. 1. Modular preparation of \(-\text{S} \equiv \text{N} = \text{S} \equiv \text{N}\). In this proposed synthesis of \((\text{SN})_n\), unit reactions are carried out with the growing substrate to produce molecular wires of \((\text{SN})_n\). In 2n separate steps C to D, the unattached end of the \(-\text{S} \equiv \text{N} = \text{S} \equiv \text{N}\) strand is first treated with the diimide, \(\text{I}\), and then with \(\text{SCl}_2\) \(n\) times to increase the wire length by \(n(\text{N}_2\text{S})\).
suggested that the biochemists' Merrifield method of poly-peptide synthesis be generalized and applied to a suitably prepared solid substrate. Via current computer controlled chemistry using a bank of reagents and valves, the Merrifield technique can be used to prepare a protein of ~100 amino acids in any prespecified sequence as follows:

The first amino acid is attached to a functional group on plastic balls (the substrate). Then the second amino acid is attached to the first, etc.; each time the product is collected and purified by simply collecting and rinsing the plastic

![Diagram of molecular level fabrication techniques](image)
The opportunity of utilizing molecular forces at the local level to form new patterns is illustrated schematically in Fig. 3(a) where a large flat B molecule is oriented epitaxial on a (100) surface of silicon. This B molecule might be of biological origin and in the future could be available from recombinant DNA techniques as recently described by Ulmer.\textsuperscript{10,11} If properly engineered at the molecular level such a B molecule with B–B edge interactions would form an epitaxial layer like Fig. 3. Note however, that the B molecules are purposely not area filling thereby providing an opportunity for forming a new pattern by filling those empty areas A with another material or molecule. A variety of techniques for depositing A are available, e.g., sputtering, vapor deposition, electrochemical transport, or cytochemical staining.\textsuperscript{12} After the A sites have been filled the large B molecule might be removed by first breaking it into smaller pieces by photolysis as suggested in Fig. 4 to give the resultant epitaxial superstructure as indicated in Fig. 3(c).

A rather different approach in the use of superstructures to fabricate or form patterns at the molecular level would make use of modulated structures as in Fig. 5. Modulated structures are being found in increasing numbers among the transition metal and rare earth oxides and chalcogenides.\textsuperscript{13} In general a modulated structure of a simple oxide is formed by treating the oxide in a reducing atmosphere at elevated temperatures. As small percentages of oxygen (or chalcogen) are removed the structure shears in such a way that the metal atoms are brought into close proximity forming metal–metal bonds. In Fig. 5 these are indicated schematically as vertical

![Diagram of molecular lithographic details](image-url)

**FIG. 4.** Molecular lithographic details. The large B molecule should be designed to be readily broken down into small pieces for easy removal after deposition of the A groups.

In this way a different amino acid can be inserted at each step. Finally, the bond of the first amino acid to the plastic ball is chemically cleaved and the released polypeptide collected.

Generalizing this technique let us imagine that a substrate is lithographically prepared so that by a series of reactions, layer by layer, conducting “molecular” wires are built up in some areas while in other areas insulation is added. At the appropriate time then, switching and control functions are added, adjacent components are bonded together, and the process continued, ultimately forming a three dimensional solid array of active and passive components.

As an example of modular or the generalized Merrifield approach, consider Fig. 1 where the preparation of molecular wires of (SN)\textsubscript{n} is proposed. This scheme is based on the preparation of oligomers of (SN)\textsubscript{n} from a sulfur diimide and SC\textsubscript{1}2 by J. Milliken.\textsuperscript{9} In Fig. 1(a) a conducting silicon surface, prepared by bombardment with SC\textsubscript{1}2, is reacted with the diimide I to produce a short chain of -(SN)- terminated with a trimethyl silicon group. This group can then be replaced by –SC\textsubscript{1} with sulfur dichloride to give Fig. 1(c). Then by an alternating sequence of first the diimide, S[NSi(CH\textsubscript{3})\textsubscript{3}]\textsubscript{2}, and then SC\textsubscript{1}2, the two reactions above can be repeated, each time extending the (SN)\textsubscript{n} chain by -(NSNS)-. Hence in these two reactions we are exhibiting a modular sequence in which the modulus -(S\textsubscript{2}N\textsubscript{2})- is produced. Note that the diimide and SC\textsubscript{1}2 are never present simultaneously. In a similar way condensation reactions might be employed to produce molecular wires of transpolyacetylene, [CH\textsubscript{2}]\textsubscript{n}, as in Fig. 2(b).

The above generalizations of the Merrifield technique then produces in special areas only molecular wires of (SN)\textsubscript{n} or [CH\textsubscript{2}]\textsubscript{n}, and hence might be thought of as an area specific MBE technique. However, by making use of the concepts of self organization much more efficient fabrication techniques are suggested by the work of Stillinger and Wasserman\textsuperscript{9} especially for insulation.\textsuperscript{10,12}

**III. MOLECULAR EPITAXIAL SUPERSTRUCTURES AND MODULATED STRUCTURES**

![Diagram of modulated inorganic structures](image-url)

**FIG. 5.** Modulated inorganic structures with a periodic distribution of conducting paths (vertical dotted lines) might be used as a sandwiched substrate for electrically linking two layers of components (a), or as a lithographic template (b).
dotted and pictured as forming a continuous conducting path. The separations between such filamentary conducting paths might vary between a few angstroms as in some NiAs-type structures to hundreds of angstroms. While a suitable material cannot be pointed to at this time these materials would seem to be an area of considerable potential use.

For example, two layers of semiconducting components might be positioned on opposite sides of such a modulated insulator so that the conducting filaments might electrically link the two sides. As suggested in Fig. 5a, conducting pads might overlap more than one filament enhancing conductivity and easing the problem of registration. By coating one side of the modulated material with a conducting film one might electrochemically form a regular array of active sites on the opposite side for the disposition of metal pads or a specific reagent leading to the preparation of molecular wires. Of course, the conducting film could be removed later and another pattern formed.

IV. ELECTRON TUNNELLING AS AN MED SWITCH

In order to achieve logical operations at the individual molecular level, that is, to achieve molecular addressability, one needs not only a direct line of communication as is suggested in Fig. 2 but also a corresponding set of switches to differentiate between functional units. In this and the next section three different phenomena operating at the molecular level are discussed as switches. These phenomena are (1) electron tunnelling through short periodic arrays, (2) soliton switching, and (3) soliton valving.

Electron tunnel switches are based on the early quasiclassical results of Pschenichnov. He suggested that the transmission coefficient of an electron approaching a finite series of periodic barriers would be unity if the electron energy matched exactly a pseudostationary energy level of the barriers. This is illustrated in Fig. 6(a) where the energy of the electron approaching the barriers from the left matches the upper resonant level of the wells. The tunnel switch can be turned off by either changing a barrier height or the depth of a potential well so that the associated pseudostationary energy level no longer matches the other levels and the energy of the incoming electron. Figure 6(b) illustrates schematically four control groups (CG) on the body of a tunnel switch that are positioned to control the depth of the potential wells. In comparing Fig. 6(a) and 6(b) we note that the potential well is associated with the quaternary nitrogen \( N^+ \). Of these four control groups in CG1 and CG3, the quaternary nitrogen charges are stationary. However, in control groups CG2 and CG4 the positive charges can move away from the tunnel body as indicated for the cyanine dyes below:

![Cyanine Dyes](image)

In Fig. 6(a) if the charge is moved to the upper nitrogen in either the second (b) or the fourth (d) control group then the associated electric field (dipole) is dramatically changed and any electron tunnelling through the body would be switched off. By having different amounts of conjugation in the control groups of Fig. 6(a), that is by varying \( n \) (as in the cyanine dye example above) the charge of different CGs can be shifted by photons of different energy. Thus Fig. 6(a) would be a molecular NAND gate analogue with optical inputs. Alternatively the charges could be shifted by the motion of a nearby charged soliton as suggested by the author recently (WMED2).

Finally we note that a variety of molecular analogue gates have been proposed, and Pschenichnov’s quasiclassical solution has been supported by an exact analytical solution for square well potentials. Recently the predicted switching action was computationally verified (WMED2). However, Barker et al. noted that long delays could be produced in the transport of the electrons through the body by trapping them between wells. This effect may be an artifact of the rectangular walls of the square well model.

V. SOLITON SWITCHING

While conformational changes, that is changes in bond angles and distances, are significant in electron tunnel switches they are of fundamental importance in both soliton switching and soliton valving.

The soliton is a nonlinear disturbance which behaves like a pseudoparticle and travels in a dispersive medium but without being dispersed. The soliton of special interest here is primarily an excited electronic state associated with zero, one, or two electrons occupying a \( p-\pi \) orbital in a conjugated system with the associated soliton charge of \( +, 0, \) or \(-\) and of spin \( 0, \pm 1/2, 0 \), respectively.
In Fig. 7 a radical soliton traveling from left to right is schematically indicated. By comparing the slope of the double bond on the right and left of the soliton, it will be noted that the soliton passage effectively interchanges double and single bonds. In this regard the soliton is comparable to a moving domain boundary in a crystal; the effective soliton size however, is several times longer than that suggested by Fig. 7.

Prior illustrations of a soliton switch involved imbedding an organic chromophore in a transpolyacetylene chain such that they shared bond conjugation. However, such a switch can be schematically illustrated, Fig. 8, as four communicating lengths of transpolyacetylene. Of the fifteen conceivable ways of sending a soliton from one end to another end (length) of transpolyacetylene, seven are prevented by the tetravalency of carbon. The eight allowed soliton paths are indicated in Fig. 8 where a soliton path $ab = ba$. As a pseudoparticle a soliton's momentum is a constant of motion; this suggests that the primary paths of interest should be represented in Fig. 8 by the direction $ac$ and $bd$. Only the fourth configuration in Fig. 8 permits both $ac$ and $bd$ soliton propagation paths. However, a soliton path $bd$ changes the configuration to $3$ which does not permit an $ac$ soliton path. Hence the $bd$ propagation switches off the $ac$ possibility until a second $bd$ soliton restores the switch to configuration $4$. A soliton path, like $ac$ in $3$ of Fig. 8, is recognized as being switched off when the conjugation is broken as by two or more successive single bonds.

Figure 9 illustrates the incorporation of two different chromophores across two transpolyacetylene chains. While the second chromophore is subjected to photoactivation, as shown, the first chromophore to the right has been switched off by chain $1$. A soliton propagating through chain $1$ will switch on the first chromophore and switch off the second chromophore; while a soliton in chain two will switch off both chromophores. This concept is readily extended to three chains and eight chromophores with an associated demultiplexing table. Packing considerations suggest that switch densities can be as high as $10^{19}/cc$.

While not considered in detail here, soliton values are closely related to soliton switches and configurations of them have been suggested as elementary but multistate cellular automata communicating via soliton propagation. However, it should be noted that M. Groves in following a more traditional approach has illustrated how soliton valves can be used to generate OR and AND gates, inverters as well as fanout memories (WMED2).

**Fig. 7.** Soliton transport. A moving soliton in a conjugated trans-(CH)$_2$ chain interchanges carbon–carbon single and double bonds. However, in cis-(CH)$_2$, Fig. 7(c) soliton propagation is unlikely because per unit length molecular orbital calculations indicate the right hand side is more stable than the left side. In both parts (a) and (c) a hydrogen atom bonded to each carbon is understood as per the tetravalency of carbon.

In the following three sections new considerations related to fabrication at the molecular level are given. These ideas were either presented at or inspired by presentations at WMED2.

**VI. BIOLOGICAL OPPORTUNITIES FOR PATTERNING**

Opportunities for fabricating both MED components and machinery and structured substrates using recombinant DNA and monoclonal antibody techniques, respectively, have been recently discussed (WMED2). However, of more immediate interest here, are some suggestions of Ulmer (WMED2). The possible use of two dimensional crystallized biological materials for the generating of patterns at the nanometer size level is indicated by the square pattern in Fig. 10. This electron micrograph of the spore heads of the influenza virus neuraminidase clearly indicates the possibilities. The unusual square arrangement of the heads ($\sim 100$ Å across) is obviously the result of interparticle bonding forces and supports the earlier suggestion of superstructuring in Figs. 3 and 4. Useful nanometer structures might be derived from such biological patterns by either well-known cytochemical deposition of heavy metal insulators or conductors, electrochemical deposition, evaporation, or sputtering.

**Fig. 8.** In this simple soliton switch the eight arrows indicate allowed soliton paths. Seven of fifteen possible paths are switched off. Only the fourth configuration permits paths $ac$ and $bd$ associated with no direction changes.

**Fig. 9.** Early example of soliton switching (5) involved two chromophores and two transpolyacetylene chains. The second sulfur chromophore can be photoactivated but not the first in the configuration illustrated. The dotted vertical lines are meant to suggest that the chromophores are $100-200$ Å apart to prevent crosstalk.
FIG. 10. The two-dimensional square array shown in this electron micrograph is composed of the 100 × 100 × 60 Å spore heads of the influenza virus neuraminidase. Note the striking similarity to Fig. 3. (Micrograph kindly supplied by D. C. Wiley, Biochemistry, Harvard, and N. Wrigley and E. Brown.)

Ulmer also drew attention to the imaginative patterns of the Dutch graphic artist Escher as in Fig. 11. In discussing part a of Fig. 11 he suggests that by proper design the various components of a device or processor could fit themselves together very much as the salamander tiles of Escher's drawing. Alternatively, in an extension of the above Sec. VI, the different tiles could represent different active components or kinds of cellular automata. 20,22

In regards to Fig. 11(b) on the right, attention was drawn (1) to diminishing size of the salamander tiles as they filled the figure center and (2) their (inexact) relationship to the mathematical concept of fractals. In fractals ever smaller sections of a pattern can have dramatic similarities to the overall larger patterns (i.e., a pattern repeats but with a scale change; as in some cellular automata patterns). 22 In the following two sections we will see (1) that this "fractal" drawing of Escher [Fig. 11(b)] might be useful in bridging the communication gap between the macro and the molecular; and (2) that scale changes in patterns might be achieved by chemical means through "organizing" molecules in Langmuir-Blodgett films.

VII. BRIDGING THE GAP WITH FIBERELECTRONICS

In borrowing an idea known to every glass blower and commercially used in the manufacturing of electron multiplier channel plates, D. Nagel has recently suggested (WMED2) 27 a potentially important electrical link between the macroscopic world and the nanometer world. The essence of his suggestion is indicated in Fig. 12. A hollow glass tube (2 mm diam) filled with metal is centered in a bundle of 20 glass rods and reduced in size by hot drawing, by a factor of 100. A new bundle (Fig. 12, center) is formed of these conducting fibers and other glass rods and again drawn down by a second factor of 100 in a hot flame. As Nagel points out: (1) the original metallic conductor has been reduced to a conductor 100 Å in diameter; and (2) the large end of such bundles could be terminated with a connector in much the same way fiber optic bundles are currently terminated. After polishing the bundle square, the conducting fibers in the small end might be exposed by selective chemical etching. While Nagel's concept is as yet untested and the composition of a conducting alloy, which will not "localize"
in the reduced metal fibers (100 Å diam), is as yet undetermined; it is an attractive idea in bridging the gap between the macro and the molecular world with electrical conductors.

By comparing the small end of the bundle, in Fig. 12 right, with Escher's fractal tile drawing in Fig. 11(b) we might imagine that the large outside salamanders might correspond to electrically conducting pads to be joined to the smallest conducting fibers.

VIII. LANGMUIR–BLODGETT FILMS AS TOOLS FOR MOLECULAR ORGANIZATION

The classical studies of Langmuir and Blodgett (L–B) of long chain aliphatic soap films on a water bath surface are of renewed interest because of their potential impact on electronic and superconducting devices. By compressing the surface films with floating barriers the early workers (for a review see Ref. 28) found that monomolecular layers could be formed on the liquid surface and then transferred to a glass substrate by withdrawing it vertically from the liquid. On withdrawal the hydrophilic group (–COOH) adheres to the substrate surface while the aliphatic groups, (CH₃)ₙCH₄, are packed in a linear formation approximately normal to the surface. By repeated dipping, while maintaining the surface pressure, multilayer-to-head, tail-to-tail layers can be formed. More recently Kuhn 29 has made use of the precise thickness of L–B monolayers to study photon and electron transfer rates as a function of distance. In this work he has introduced the use of larger functional groups such as the electron acceptors and cyanine dyes (as below) in place of the usual hydrophilic carboxylic acid group, –COOH. Note that in order to maintain good packing relationships, two aliphatic hydrophobic groups are attached to each of these larger polar groups.

In a related context, the electrical properties and the organization of lipoid bilayer of biological origin are of considerable interest, especially in those membranes that demonstrate an electric field dependence of Na⁺ and K⁺ ion conductance. G. Baumann, G. Easton, S. Quint, and R. Johnson (WMED2) 30 have recently elaborated on a theory of such membranes which (theory) depends upon the incorporation of small clusters of special rod shaped proteins into the membrane in the presence of an electric field. These authors suggest, as in Fig. 13(a), that one side of the rod is hydrophobic and the other hydrophilic, as might be achieved in an α-helix with the proper sequencing of amino acid residues. However, in the presence of an electric field these rods are drawn into the lipoid bilayer in small clusters (n = 2 to 4). Note that the center of the cluster can be hydrophilic and hence act as a switchable ion channel for Na⁺ and K ions when the electric field is at the right strength. We will now combine the ideas of Kuhn and Baumann in order to achieve a higher organization of Langmuir–Blodgett films.

While pinhole free L–B films are necessary for their use as insulators in MOS and Josephson junction devices for lithographic purposes, it might be desirable to have regular periodic variations in the L–B film. By preparing films of two components of different solubility, early L–B workers 30 and absorbed film specialists 31 have been able to prepare "skeltonized" films with random holes.

A regular array of holes (or other features) might be achievable using the organizing molecules of Fig. 14. In the simplest case, the organizing molecule consists of two linked hydrophilic groups (cyanine dyes) each containing a long chain aliphatic group and a bifilic rod shaped group of an appropriate length. In Fig. 15(a) we indicate how the simplest organizing molecule might be used to prepare a L–B film with a hexagonal variation of properties. If the components of the soluble complex (indicated by the large circles in Fig. 15) can be later removed then one would have a periodic structure of holes. As Fig. 15(b) indicates, a change of composition should lead to other structures, in this case an increase in hexagonal cell edge by the factor of \( \sqrt{3} \).

This variation of 2-d cell size with composition reminds one, in reverse, of Escher's drawing, Fig. 11(b) (right), where ever diminishing salamander tiles are employed. A similar effect can be achieved by the use of a different size of organizing molecules. This is indicated schematically in Fig. 16.
FIG. 13. Molecular switching in membranes. To explain ionic conduction through lipoid bilayers Baumann and his co-workers (Ref. 30) suggested that rod shaped protein molecules with one side hydrophilic and the other hydrophobic as in Fig. 13(a), are drawn into bilayers in the presence of an electric field to form a hydrophilic channel [Fig. 13(b)].

where a square lattice is employed. [Square and hexagonal lattices will probably prove to be too symmetric.] After the square lattice of cell edge L is formed, the introduction of the larger organizing molecule with other composition changes should give rise to a doubling of the L–B film cell dimensions as indicated in Fig. 16(b).

The examples of this section suggest that: (1) principles which are responsible for order in biological systems can be employed to order L–B films and other molecular assem-bilages; and (2) changes in organizing molecules and composition can result in pattern changes imitating those found in the study of fractals.

IX. STITCHING TOGETHER MONOMOLECULAR LAYERS

Once a monomolecular layer or multilayer film has been assembled, its structural stability can be greatly enhanced by solid state polymerization of built in functional groups. A
variety of functional groups can be used, including vinyl acrylates, \( \alpha \)-amino acids, \( \beta \) diacetylenes, nitriles and terminal acetylene groups. Of particular interest for solid state reactions are those functional groups that polymerize without the release of any by-product that could disrupt the solid assembly. Intralayer polymerization of diacetylenic groups by UV light or \( \gamma \)-radiation has been used to stabilize L–B films for most of a decade\(^3\) and is illustrated on the right of Fig. 17.

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**Fig. 14.** Organizing molecules for L–B films. Combining the ideas of Kuhn and Baumann the author proposes that a series of molecules can be prepared that uses weak van der Waals and dipole forces to organize L–B films.

**Fig. 15.** Organizing L–B films. The use of organizing molecules and a variation in composition is expected to result in periodic 2-D structures of different cell sizes. The unit cell length in Fig. 15(b) would be \( \sqrt{3} L \).

**Fig. 16.** Fractal cell changes. In a square unit cell organization of a L–B film a change in both composition and organizing molecules could give rise to a doubling of the unit cell length.

**Fig. 17.** Polymerization scheme. The polymerization of terminal acetylenic (or nitrile) groups, as on the left, could be employed to bond together two monomolecular layers. However, the polymerization of internalized diacetylenic groups is frequently used for intralayer stabilization.
On the other hand polymerization of acetylene terminal groups, Fig. 17 left, common to two monolayers and located at their common interface can result in interlayer polymerization. Thus, not only can a monolayer be stabilized by stitching neighboring molecules together but adjacent monolayers can be covalently bonded together as well. However, it should be stressed that in order for such in situ or solid state polymerizations to take place without disruption of the structure the reacting neighboring groups must have the correct conformations and the right positional relationships to each other.

With regard to soliton devices, we note that a moving soliton is not supported by the product of a diacetylene polymerization since a soliton propagation would convert the acetylenic product (Fig. 17, right, middle) to the nonequivalent, usually more energetic, cumulenic form. On the other hand polymerization of the terminal acetylenic groups, Fig. 17 left, result in a transpolyacetylenic product that should support soliton propagation.

Using Co(II) as a radiation source, Lando and Thakur (WME2D) recently reported on the bulk polymerization of a single crystal of the dimer of 1,11-dodecadiyne, a monomer containing both diacetylenic and terminal acetylene groups. The resulting single crystalline produced contained alternating parallel olefinic and acetylenic chains (as in Fig. 17) linked together by aliphatic-(CH2)n=groups into a sheet structure. This result is important not only because it represents a case of both intra- and interlayer stitching but it also provides a bulk sample for the determination of soliton propagation velocity. A direct measurement of soliton velocity would constitute a substantial soliton existence proof which is not available from measurements involving bulk polyacetylene.

X. SUMMARY

While the recognized need to control the morphology and organization of molecular electronic devices provided the initial impetus for the above considerations, we hope that this paper has been of heuristic value in regard to rich possibilities for fabricating useful structures at the nanometer and molecular size level. A quick partial listing of the topics covered, Merrifield synthesis, modulated structures, electron tunnelling, naramidase, L-B films, ferroelectronics, fractals, and monolayer polymerization is enough to suggest that future fabrication techniques will not be a respecter of the boundaries of traditional disciplines. It is equally clear that while technical advances often seem serendipitous in nature one must prepare for such future events in the area of molecular level fabrication by a continued and penetrating examination of chemical and local bonding forces and effects.

\[\text{[d]}\] F. L. Carter, in Molecular Electronic Devices (Dekker, New York, 1982).
\[\text{[g]}\] R. C. Haddon and F. H. Stilling, ibid., p. 19.
\[\text{[k]}\] K. Ulmer, in Molecular Electronic Devices (Dekker, New York, 1982), p. 213.
\[\text{[m]}\] S. Hankaer and B. L. Giammarra, in Molecular Electronic Devices (Dekker, New York, 1982), p. 181.
\[\text{[q]}\] F. L. Carter, in Molecular Electronic Devices (Dekker, New York, 1982) p. 344.
\[\text{[w]}\] W. Kohler, Rev. Mod. Phys. (in press).
\[\text{[y]}\] K. E. Decker, ibid.
\[\text{[z]}\] H. M. McAleney and J. M. Wehrung, ibid.
\[\text{[a]}\] K. Ulmer, ibid.
\[\text{[b]}\] D. J. Nagel, ibid.
\[\text{[c]}\] A. R. Bishop, ibid.
\[\text{[d]}\] F. H. Stilling, ibid.
\[\text{[e]}\] H. M. McAleney and J. M. Wehrung, ibid.
\[\text{[f]}\] M. P. Groves, ibid.
\[\text{[g]}\] K. Ulmer, ibid.
\[\text{[h]}\] K. Ulmer, ibid.
\[\text{[i]}\] ibid.
\[\text{[j]}\] ibid.
\[\text{[k]}\] ibid.
\[\text{[l]}\] ibid.
\[\text{[m]}\] ibid.
\[\text{[n]}\] ibid.
\[\text{[o]}\] ibid.
\[\text{[p]}\] ibid.
\[\text{[q]}\] ibid.
\[\text{[r]}\] ibid.
\[\text{[s]}\] ibid.
\[\text{[t]}\] ibid.
\[\text{[u]}\] ibid.
\[\text{[v]}\] ibid.
\[\text{[w]}\] ibid.
\[\text{[x]}\] ibid.
\[\text{[y]}\] ibid.
\[\text{[z]}\] ibid.
\[\text{[a]}\] ibid.