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# Protecting Devices by Active Coating

(A method to build a signature based microsafe)

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**Abstract:** The presented paper demonstrates a method to embed a unique signature into a coating material used in a smart card or in the covering material of some other secure hardware device. The method bases on the impossibility of exactly reproducing a specific piece of plastic or other material used to cover the secure hardware. By using a very inhomogeneous materials or mixtures of conductors and insulators such a cover is made unique by the method of production. This inhomogeneous piece and the non-reproducible and random properties are incorporated into an electronic signature which is checked whenever needed. Assuming that the surface is covered totally with an "active coating material" it is impossible to partially penetrate or destroy the coating without destroying the signature. Unpenetrable hardware is an inevitable element in nearly all secure designs and with the promotion of digital signatures such unpenetrable hardware becomes even more important. The result gained with the presented work is the possibility to make a hardware unique depending on randomness, and to assure that penetration is not only detected but also features logical destruction of the secure hardware [PAT96]. Implementing such penetration sensors with memory enhances the security to a large extent, and since the destruction upon perceived penetration is logical there is no possible false alarm.

## 1 Introduction

This document assumes a computing device whereof a distinct part contains relevant secure information that has to be guarded by special means. It further assumes that this distinct security module *SM* is well separated from the rest of the hardware so that it is possible to take design measures which allow detection, monitoring, prevention and reaction on an external attack to the module. The paper concentrates on features of design and construction of such an *SM*. Security of peripherals as well as modules outside to *SM* are not addressed.

The overall structure may be seen as shown in figure 1. Special attention is paid to the security module *SM* and to methods of how to implement security guards *G*. The first observation which can be made is that the task of secure designing is smaller when the diameter of the security module gets smaller. In practice this means that security keys and application of security keys (encryption, decryption and signing) will define the size of the security module in many cases. This observation is based on a second assumption which says that security design primarily concentrates on the controlled use of the security module and on the leakage of information from this module but does not widely address aspects of theft and destruction of the module as long as there can be assured that stolen modules or broken modules do not deliver secrets. This assumption is consistent with the fact that data as bits do not have a value but only data as content define a specific value.

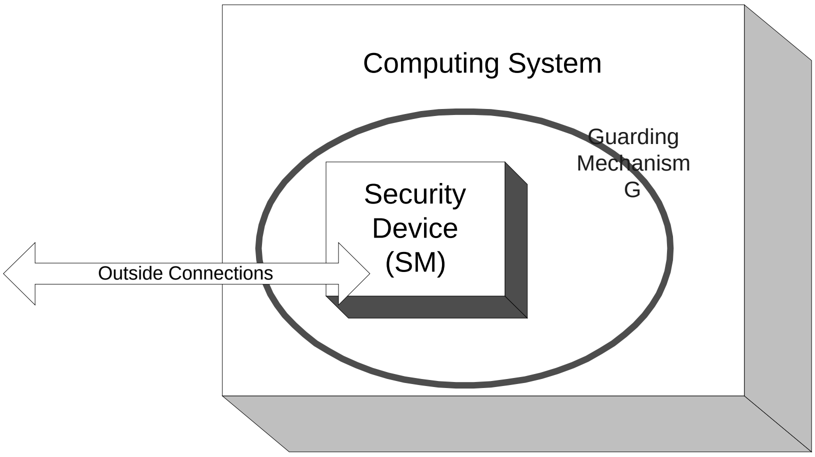



Figure 1: The setup of the discussed computing environment.

A second aspect is governed by the question “At what times should protection be in place?” The answer seems obvious: protection should be effective any time when there is valid and usable information within the module. Still, we may distinguish at least three situations:

1. ***Cold***: the security module is not powered at all. This is the case at least during long term storage usually before the first use. For

some systems like smart cards this situation also occurs between regular use with information in the module. This seems to be the most critical situation as the security features are passive in this case.

2. ***Warm***: the security module is minimum powered. Only the main security features are turned on and the security guard *G* is actively protecting part or all of the module.

3. ***Hot***: the security module is operating and powered with the security guard *G* operating as well.

It is obvious that the amount of security does not depend on the status of a device, but mostly on the security information a possible attack could reveal. But the effort of guarding mechanisms could be totally different in different situations.

Typically the largest amount of information present and eligible for an information guard will exist in a *hot* device. The status *warm* only exists in special devices at all where a buffering of power is possible to maintain vital functions. With such devices a minimum power usually is applied during life time of the device. Even if this seems to be the most favorable condition for guarding when some activity may be assumed, at any time one has also to consider devices where power is completely off during long phases, and possible attacks happening during this time. This *cold* device situation has to be faced with all smart cards. The fact arises from standards [ISO89] which de facto ask for a single component solution giving no place for power supply for buffering. Since smart cards are discussed in the context of digital signatures, the *cold* situation seems to be the most important one.

In practice, we observe that the security systems considered for wide applications suffer various security problems.

## 2 The Model

As seen from figure 1 we concentrate on the core of a system which we assume to be well separated.

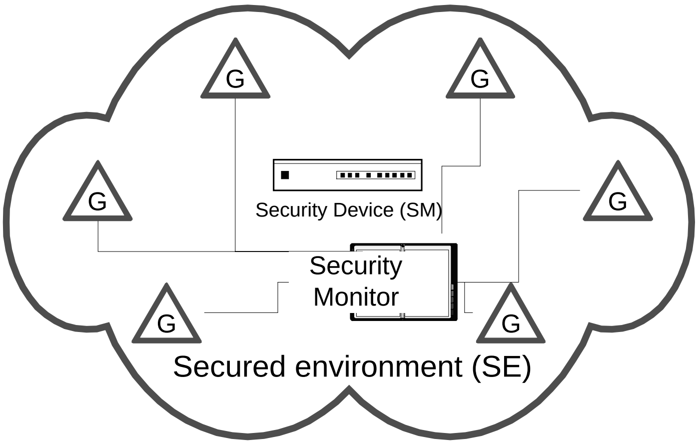



Figure 2: Security device with guards.

Around the module *SM* security guards *G,* i.e. sensors, are allocated to register different types of abnormal conditions. These sensors report to a security monitor. A set of conditions as sensed by the various *G*s is defined as valid operating conditions *OC*. Any violation of *OC* is assumed to be seized, and an according security response *SR* is assumed to take place after a predefined reaction time $T_r$.

This model describes a closed shape *S* of many dimensions enclosing some device *SM*. An attack can be viewed as trace propagating at some speed *v* towards the center where the module *SM* is assumed. As long as the total time $T_r$ from recognition to measures taken at any moment is less than the minimum distance from the entry point through guarded shape S to the module *SM* divided by the maximum possible speed, the situation is seen as safe.

With the different possible states of a module *SM* in mind it is important to look at the situation as a dynamic process. Furthermore it is useful to add the dimension of cost, as done later on, in this context.

A *successful attack* is an attack leaking or altering information of the module *SM* without the defined countermeasures being taken in due time. Some of the possible scenarios of an attack are pointed at below. This is done to demonstrate the large diversity of possible attacks and thus the complexity of the matter. Basically there are two categories of an attack:

A) *Non destructive attacks*: in this case the module *SM* is observed from outside and gathered information is misused. The module *SM* stays operable, and in the optimum case the presence of an attack cannot be seen on the module after the end of the attack. Attacks destroying some of the guarding mechanisms are included in this attack intentionally.

B) *Destructive attack*: such attacks will destroy the module, but some or all of the information which was designed to be secret to *SM* will be compromised. This attack is much less severe and sometimes is assumed to be overcome by logically unique devices. This method of unique devices by only using unique key information is a common technique in the field of smart cards. For reasons of consistency an attack which gathers all or most of the secret information in an way that a non-distinguishable device *SM** is generated and replaced has to be classified as a possible non-destructive attack. This is due to the fact that this discussion concentrates on information.

Generally it would be possible to distinguish between attacks addressed towards hardware and those addressed towards software. This distinction is not extremely useful in practice, as most attacks combine both domains.

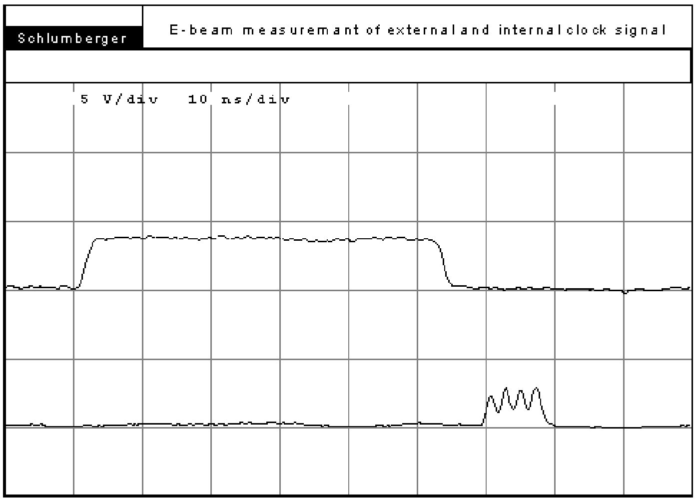



Figure 3: E-beam analysis of a 450MHz digital signal.

From the technical point of view the discussion presented focuses on the following categories:

I. *Observation of primary and secondary effects*: this includes data communicated, sequences, crosstalk, radiation, etc.

II. *Modification of operating conditions with the goal to change the internal function*: this category includes temperature, power supplied, frequency, radiation, light, etc.

III. *Measuring and injection of signals internal to circuits*: in the context of smart cards this would include probing with conventional methods, electronic beams, focused ion beams, etc.

Even if a special attack like injecting and probing of signals at extreme temperatures would fall into several categories, it seems to be useful to use such categories since measures to be taken are quite different along with the various categories.

To give an idea what the state of the art makes possible in special cases, figure 3 shows an E-beam analysis of high frequency signals. In this special example a high frequency signal was analyzed. The result of this example shows that signals even at extremely high frequencies can be intercepted if no specific measures of protection are employed.

Since it may be assumed that expensive attacks are only performed when the revenue from the attack is adequate, it is essential to draw a limit $V$ for a special module $SM$ , reflecting the amount of money this module is able to protect. This observation is quite obvious to reflect in monetary systems, but becomes a lot more complicated in medical systems or in systems of personal safety or national security.

## 3 The Formulation of the Problem

As we are considering device security against compromise by hardware analysis, we can formulate the specific security problem the following way:

$C_{sec}$ Cost of the security enhancing technology.

$C_{analyse}$ Cost of a successful analysis.

$V_p$ Value to be protected by the respective security technology.

- Security is viewed as manageable in business terms if the condition $C_{sec} << V_p$ is satisfied.
- A system is viewed as secure in the special context if the condition $C_{analyse} >> V_p$ is satisfied, or in some cases $C_{analyse} >> \Sigma(V_p)$, where $\Sigma(V_p)$ is the total of all values secured with the respective technology, is satisfied.

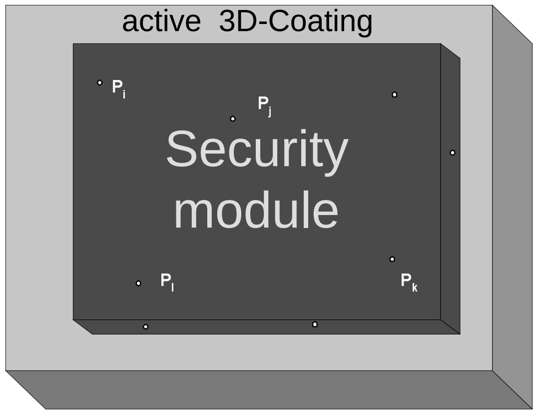
The arising problem in all these cases is that the condition resulting from the above $C_{analyse} >>> C_{sec}$ is generally quite complicated to match when looking at hardware components. The situation becomes even more complicated if the values secured with the technology cannot easily be measured in terms of money. In this case a value $V_p$ could be substituted.

## 4 A Method to Inhibit Physical Access

Having stated the problem of securing hardware, this chapter concentrates on a method to implement guards for electronic devices. The security target is to inhibit secret information from leaving the security boundaries or being altered. In this context, securing a hardware is assumed to be successful if relevant information can not be altered or extracted by an aggressor. The presented method targets primarily VLSI chips like those used within smart cards. However, the general principle can be applied to other electronic devices containing at least a processor or using a processor to perform the guarding operation in a similar way.

Smart cards are for the time being quite in danger to be exposed to “microprobing” and similar methods. To prevent for this regulations like the FIPS 140 [FIPS94] demand for special covering for such devices in order to inhibit etching a cover and getting access to an operable device exposed for analysis.

The method discussed with this paper does not prevent analysis as such, but uses a coating mechanism that can be classified as a sensor with memory and storage for key information. Tampering with this type of coating leads to a change in the key information and thus tampering destroys such key information. This key information is used to decrypt [SCHN96] critical information to yield the useful information. Such decryption can only be performed in a *hot* state as classified above. This leads to the situation that the overall security is the security implemented in the hot state.




a) Security module (red) (*SD*)
b) Secure coating (grey) (*M*)
c) Security guards ($P_i$)

Figure 4: An encapsulated secure unit.

Figure 4 shows a general three-dimensional model of a coated security device. This security device denoted as *SD* is shown with the coating *M* and the security guards $P_i$ on the surface of the unit *SD*. The basic assumption is that by using appropriate mixtures or materials, the coating shown in grey may be implement in a way resulting in random electrical properties like resistance and capacitance. A geometrically identical duplicate will this way have different electrical properties. Removal and re-application of the coating similarly is assumed to change electrical properties of the coating.

This unique coating characterizes the specific device. And from this characterization a device signature *ST* is derived.

### 4.1 Components of "Active Coating"

1. Be (*SD*) a unit like a smart card to be secured, then the measure shall detect manipulation both during operation and during off-powered storage, and information shall not leak in any situation by design.

2. Be (*M*) some coating to secure *SD*. Such coating is assumed to be of a material that has an electrically measurable property (like resistance or capacitance), but is highly inhomogeneous and irreproducible.

3. ($P_i$) are spots on the surface that can apply some signal or measure the value of the property.

### 4.2 The Pi Spot

The *Pi* spots are designed to apply and measure electrical properties. In case of a smart card the spots $P_i$ are areas somewhere on the chip surface that look like pads but are as small as technology allows. This way these spots contact to the inhomogeneous coating material. The I/O pads and power pads themselves are assumed to be covered by an insulating material after ponding. In the simplest case, a $P_i$ may serve as output switching either some stable reference *Vref* or *VSS* to the $P_i$ spot, or as input sensing the voltage via an analog switch by usage of an analog busline connected to an A/D converter. This gives the possibility to select an arbitrary spot for sensing out of the available spots. This situation is shown in figure 5a.

### 4.3 Signing the chip coating

Using different spots with different output values $m_i$ and combining the respective input values $s_i$ using an appropriate function $ST = f(m_i, s_i)$, coverage over the surface shall be achieved so that tampering at any spot on the surface will at least change one of the relevant inputs significantly. As *f()* can be chosen as a hash function, selective tamper is impossible. If needed, temperature may be compensated by setting different temperature intervals. This procedure assumes that the sensed values $s_i$ are not too close to a value that changes with a small variation in a way that significant digits are changed after the rightmost digits are truncated. If this situation happens this value is discarded, and by rearranging input and output spots a more stable situation is found. As the value *ST* is kept within the device all the time, it can be used asymmetric key both for encryption during setup and decryption before use of relevant secret information and code pieces.

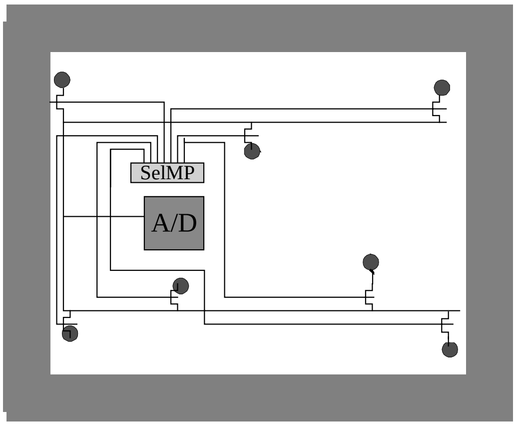



Figure 5a: Example of chip with A/D and $P_i$ spots.

## 5 How to Apply the Signature of the Coating

If temperature intervals are not necessary, the $ST$ value of the equation above may be used as a key $ST_{Norm}$. In the case of different intervals with different temperatures $\Delta ST_j$ denominates the difference between the signature $ST_{Norm}$ (e.g. at 25° C) and the signature for the temperature interval $j$. The $\Delta ST_j$ values are stored along with the output and input locations. In the course of initialization, $ST$ is used to encrypt all relevant secret information. It can also be used to sign the program code if necessary. As only differences are stored, it is assumed that theses values do not deliver information on $ST_{Norm.}$

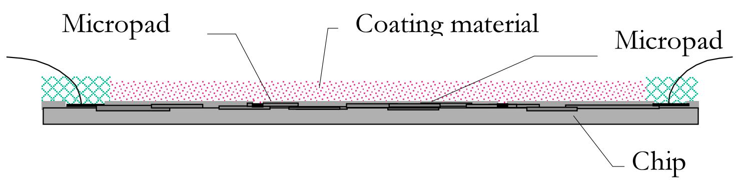



Figure 5b: Sectional view of 5a.

Step I : Determine $ST_j$ thus $ST_{Norm}=ST_j- \Delta ST_j$.

Step II: The security relevant information is decrypted using $ST_{Norm}$.

Due to inhomogeneous properties of the coating material the coating is assumed not to be reproducible. As $\Delta ST_j$ and $ST_{Norm}$ are calculated during initialization it is assumed that in a proper design this information never leaves the unit *SD*.

## 6 Scenario of an Attack

As a consequence of available design methods [WES92] the most promising attack still is to tap on signals of a given smart card design. In many cases this means that locations of signals on the surface are identified and seized with probes inserted. At the same time such locations can be used to insert signal so that the operation of the smart card is influenced in a way that information is gained by the attacker as much as possible.

a) In the presented situation the coating material is not a simple insulator. Thus, any contact between the probe and the coating material will influence the signals probed. Assuming that the resistive and capacitive properties are adequate, the influence on the signals on the chip will be such that the results are heavily distorted and the general behavior of the smart card is changed.

b) Any contact between the probe and the coating material will strongly influence the values probed by the signature mechanism of the coating. This will result in a situation where the signature is invalid and no information is acquired. This basically has the result that the area where the coating material has to be removed to make probing possible is necessarily relatively large so that contact between probes and coating can be avoided (see also figure 6).

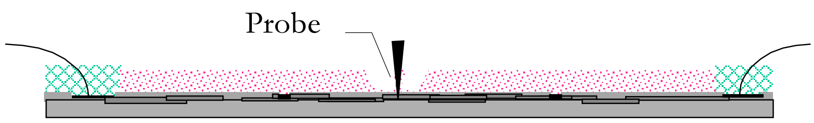



Figure 6: Scenario of a probing attack.

The figure above shows an attack of a chip guarded by active coating. In the general case it will take some effort to find a spot on the chip exactly, since non-transparent materials are assumed. The fact is that the hole to dig into the coating material will be substantially larger that in the case of transparent material.

If the $P_i$ spots are dense enough on the surface of the chip, it may be assumed that even partially destroying the coating will result in at least one value relevant to the signature being changed; thus the secret information can no more be decrypted. Removing larger parts of the coating will have at least as severe effects, and thus the coating is to be assumed secure by having an equivalent of a fraud-resistant memory.

Similarly to the probing attack, the method of active coating may be structured in a way that many aspects of a differential fault analysis are covered [DFA96]. This aspect is not dealt with in detail, but just some basic related thoughts are presented. The method strongly bases on the fact that only correctly retrieved signatures from the coating allow continuation. This is basically achieved by the potential of encrypting some of the consequently executed code. This way any fault in retrieving or applying the signature of the coating may be assumed to result in a complete faulty operation. Neither the result of the retrieved signature itself nor the result of the encrypted data when applying the signature as a key are ever seen by the outside, but stay totally internal to the device.

It is, however, obvious that all the measures necessary to inhibit DFA in consequent operations have to be taken. Repeated application of the signing mechanism can be one component in this direction. In this context it seems to be useful to take advantage of the fact that keeping parts of the results of the coating signature in the encrypted part of the device is not an extra security risk.

## 7 An Active Coating Demonstration Module

To demonstrate the effect of active coating, a demonstration module has been built. This module which is shown in the figure below uses a very small number of sensing points. It simulates only a part of a surface of a security device.

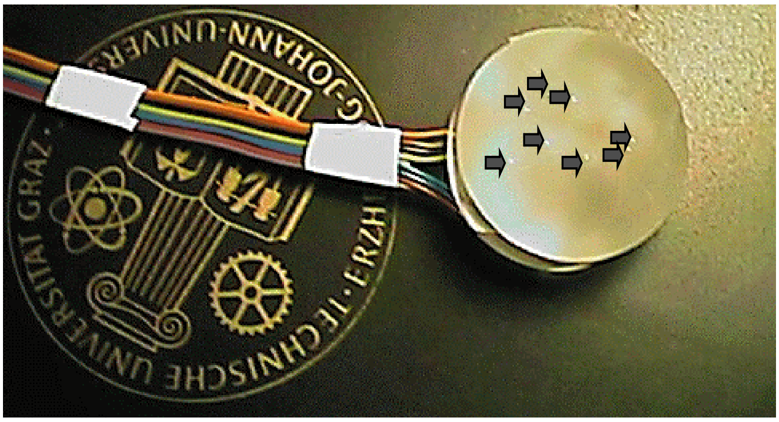
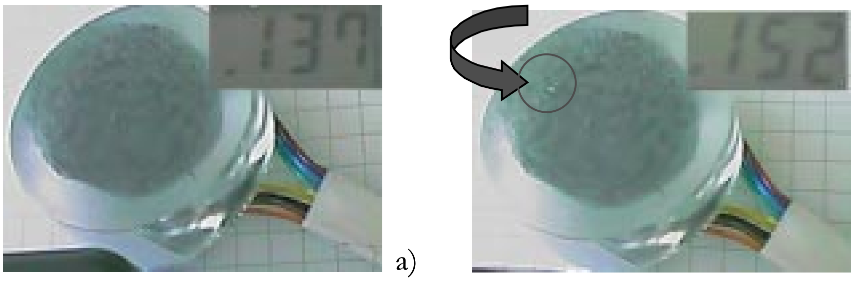


Figure 7: A coating demonstrator.

The security device is simulated by a block of resin where the micropads are the tips of thin wires. In figure 7, these micropads are pointed at with red arrows. The surface shown in figure 7 would reflect the surface of a chip where the coating should reside on. For the demonstrator the VLSI device has been substituted by a cable leading to the computer.

Coating was actually provided by using graphite and paint as an inhomogeneous material. To demonstrate the effect, the first layer of the coating material which ultimately has to have a three dimensional property is shown in figure 8. There, only the resistive property is demonstrated.

A simple violation of the device integrity is simulated by touching the coating with a metallic probe. The result can be seen between the micropads S and T. The change of the resistive property due to the integrity violation was over 10% in this case.



a) b)

Figure 8: Tampering with an active coating device.

In this simple case only 8 micropads were included. The position where tampering has taken place is shown in the circle in figure 8 b). In the practical case, the number of micropads would have to result from external observability of the coating. It is assumed that two to four bits are taken from each micropad, thus resulting in a realistic number of 30 to 80 micropads for a single chip device.

## 8 Handling Temperature and Environment

Figure 9 shows the situation of a single actuator A and the function of the shield (ground). While in practice there will be many more, this model is introduced to concentrate on the handling of environmental conditions and aging. Besides accuracy of sensing the coating properties, there are several facts to consider as the keys derived from the sensing process need to be unique and, as they are not stored anywhere, well reproducible.

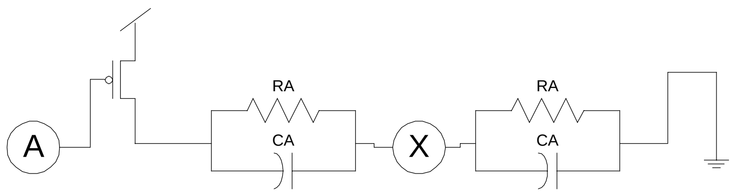



Figure 9: The sensor model.

We concentrate on two types:

1. The aging effects.

These effects will allow sensing values to migrate  slowly from an original value to an asymptotic value. I this case the main assumption is that a module, protected with active coating is not out of operation for excessive periods of time. Under this condition a feedback mechanism can be introduced so as to compensate for such effects.

2. Environmental effects.

Such effects temporarily influence the key retrieval. Temperature and humidity are obvious examples.

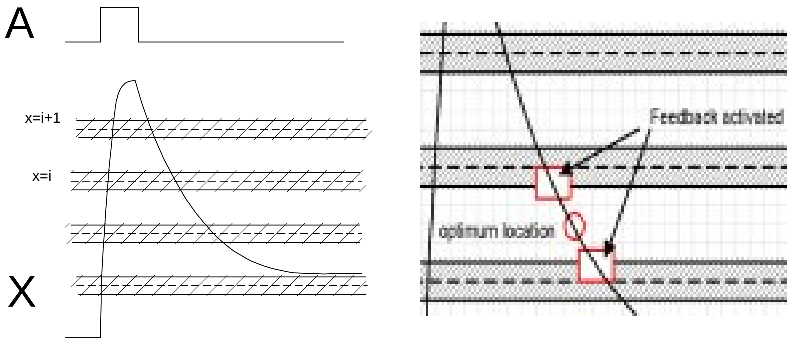



Figure 10: The critical areas.

As shown in figure 10, the described situation results in a split into sense values that may be used as they are, and into sense values that need post processing and feedback. This feedback is used to bring the sense values back into the optimum position. Feedback is done by changing the pulse width on the actuator A. As only discrete values of the sensed value X are used, and as the change in A is only used to modify the unused part of the sense value, this is not assumed to influence security.

Temperature is still a further problem. This parameter may influence in a wider range. For that reason the system assumes that a temperature sensor is included. As a result of the ambient temperature, a bias to the actuator value A is calculated or retrieved from a table. These measures are used to ensure maximum operability of the system.

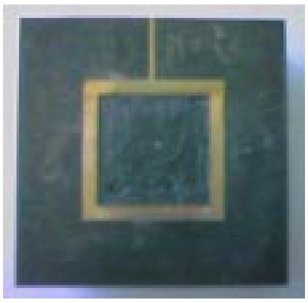


Figure 11: A Sample chip with coating.

To gather sample data and to verify the basic assumptions a sample chip has been coated with a mixture of resin silver and graphite resulting in a fairly inhomogeneous cover material. Both resistive and capacitive effects have been evaluated using this sample chip. To judge on stability the sensing points have been made available at pins on the outside.

## 9 Further Applications and Conclusion

Independent from the above mentioned, active coating can also be used for further applications associated with the application of encapsulating a security device.

a) A first application is the substitution of test fuses usually built into a smart card device to distinguish between the initial test of a device and the operation of the device. If it is assured that even during test the unique information of the coating is not delivered upon a certain procedure, the method of active coating can be used to implement fuses. The simplest way is to define the fuse to be blown if the decryption of a certain value matches a given location. If this procedure is implemented properly, this results in the perfect fuse. Even if logically reconnected by e.g. destroying the coating or partially changing the coating signature, there is no danger as all information is logically destroyed with this effect. Thereafter the device could even be reused and reinitialized from the technical point of view. From a security and systematic point of view this should not take place except when the change of the coating properties is performed in a secure environment in order to reinitialize the device.

b) A further application of the coating could be the secure transport of uninitialized devices. This is a problem with large quantities of devices.

Secure coating is not an easy problem. However, it is vital for many applications and most present designs of smart cards have to be classified as penetrable with appropriate means. Even with special chemicals used for coating it is very complicated to install coating on chips that meet the demand that tamper is also damaging the chip's function and that it can thus be made sure that secret information in not possibly acquired, active coating may contribute to this problem in a consistent way. Making cryptographically sure that any change in the coating is closing down the access to information promises to serve the purpose of building an effective microsafe in many contexts like electronic purses and smart cards for digital signatures. This method of a self-signing microsafe can also be designed to defeat many aspects of a differential fault analysis attack when applied properly.

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