I. INTRODUCTION

The notion that electron wave interference should occur in Fowler–Nordheim (FN) tunneling of electrons into thin (<6 nm) oxide layers comprising a metal–oxide–semiconductor (MOS) structure was proposed by Gundlach over three decades ago. Oscillations in the (oxide)-bias-dependent current arise from the interference of electron waves reflected at the oxide–semiconductor (OS) interface and at the point of emergence of the tunneling electrons at the bottom of the tilted SiO2 conduction band. The latter point is a “hard” turning point, whereas the OS interface is relatively transparent, with reflections occurring mainly from the wave-function mismatch across the interface. Experimental verification of a weak oscillatory structure in the FN current was reported by Maserjian and Petersson in 1974, and by others in subsequent years. Invariably, these data were analyzed in terms of Gundlach’s theory based on a trapezoidal barrier (i.e., neglecting image force effect), from which an estimation of the conduction-band effective mass $m_{\text{ox}}$ of SiO2 can be made. Values for $m_{\text{ox}}$ ranged from 0.32$m_e$ (Ref. 1) to as high as 0.85$m_e$, where $m_e$ is the free-electron mass. The conduction-band effective mass was estimated as well from fits of the theoretical FN current to experimental data covering many orders of magnitude of the current. Again, image force effects were neglected and values reported ranged from a low of 0.3$m_e$ (Ref. 9) to 0.5$m_e$. When image forces were included, the values were some-

what higher. Although a defacto value of 0.5$m_e$ is almost exclusively used in transport simulations, the reported discrepancies in $m_{\text{ox}}$ and its dependence on fitting assumptions questions the acceptance of this standard, and prompts one to look for alternative experimental methods to extract a value for $m_{\text{ox}}$. Intrinsically, interference phenomena represent the most straightforward method to arrive at a value of $m_{\text{ox}}$. Provided the inherent difficulties in the experiment and simulation of FN tunneling can be overcome. These include a position-dependent energy of the electron, uncertain tunneling (injection) description, a weak signal superimposed on a strongly rising current and averaging effects due to a large and often inhogeneous device area. These constraints, as we shall see, can be circumvented by using the local injection scheme of ballistic electron emission microscopy (BEEM). This scanning tunneling microscope (STM) based method allows the injection of variable energy and nearly monochromatic electrons into the thin gate of a MOS structure and then directly into the conduction band of the SiO2. Both the high lateral confinement (<2 nm) of the injected electrons in thin oxides (<4 nm), which enhances the attainment of a homogeneous local oxide potential, and the relatively weak power dependency on energy for the transmitted current are contributory to the realization of pronounced interference oscillations. Moreover, the modeling of transport in SiO2 for “over the barrier” injection depends on fewer unknowns than FN and direct tunneling, which assures a higher degree of confidence in the calculated parameters obtained through fits to the data. We present here both oscillatory BEEM current data for a 2.8 nm SiO2 layer and fits
using solutions of the Schrödinger equation that include image force effects, with the relevant adjustable parameter being the effective mass \( m_{\text{ox}} \) and oxide thickness \( d \). With the assumption that \( d \) is known within \( \pm 0.2 \) nm, a “best-fit” value of \( m_{\text{ox}} = 0.63 \pm 0.09 m_e \) was obtained. Uncertainties in other parameters needed for the fits, such as the built-in oxide potential \( V_{\text{ox}} \) and the effective dielectric constant \( \varepsilon_{\text{ox}} \) proved to be of minor consequence to the error in \( m_{\text{ox}} \).

II. EXPERIMENTAL DETAILS

A. Ballistic electron emission microscopy (BEEM)

BEEM is an adaptation of the conventional STM and is characterized by a special sample configuration that consists of a thin conducting layer, usually a metal, deposited on top of the semiconductor structure to be measured. Although historically a Schottky barrier, here the sample is a MOS structure. The metal provides a ground contact relative to which both the STM tip bias \( V_T \) and the applied oxide bias \( V_b \) are referenced. The tip bias thus defines the energy \( eV_T \) of the electrons injected into the metal. For metal film thicknesses comparable or less than the electron mean-free path, most of the electrons will traverse the metal and reach the far interface without scattering (ballistically). If the electrons encounter a potential barrier at that interface, they will backscatter unless their energy exceeds that of the metal–oxide barrier. In this case, a fraction of the electrons will be injected into the conduction band of the SiO\(_2\). Here, they may undergo electron–phonon scattering, which may cause some of them to return to the metal.\(^{15} \) The remainder, if not trapped,\(^{16,17} \) proceed towards the Si substrate to emerge as a collector current \( I_c \). The STM is operated under constant \( I_T \) conditions. For the experiments reported here \( I_T = 2 \) nA. In the spectroscopy mode of BEEM, the STM image acquisition is interrupted at a predetermined point on the surface and the collector current \( I_c \) is measured as \( V_T \) is ramped over a voltage range that includes the barrier potential. Initially, \( I_c \) is zero until \( V_T \) exceeds a threshold value \( V_o \) that represents the maximum in the barrier potential of the MOS structure.

An energy-band diagram for a BEEM experiment on a MOS structure is schematically shown in Fig. 1 for \( V_b = 0 \). The curved leading edge of the oxide barrier results from the inclusion of image force lowering,\(^{18} \) a corresponding, but weaker effect at the SiO\(_2\)–Si interface was omitted for clarity. Conditions for injection into the conduction band of the SiO\(_2\) are shown \((V_T > V_o)\). The threshold for injection \( V_o \) is about 4 V in the absence of a negative trapped charge.\(^{17} \) The application of an external oxide bias \( V_b \) further modifies the electron energies as they move across the oxide. In the present experiments \( V_b = 0 \), however, \( V_{\text{ox}} \approx 0.2 \) V due to work-function differences between the \( n \)-type Si and the Pd layer.\(^{18} \) It is worth pointing out that the energy distribution of electrons injected by the STM tip fall off in near-exponential fashion from its maximum value, with an energy spread that decreases with increasing energy \( eV_T \). A theoretical full width at half maximum of \( \sim 0.150 \) eV was estimated for \( eV_T = 6 \) eV.\(^{19} \) This energy spread is sufficiently monochromatic for characterizing most hot electron phenomena in oxides.

B. Sample preparation

The device-grade SiO\(_2\) layers were thermally grown near 800 °C in dry oxygen on 125 mm Si(100) wafers doped in the low 10\(^{17} \) cm\(^{-3} \) range. The wafer was subsequently annealed in forming gas at 500 °C. Working samples of \( \sim 8 \times 15 \) mm\(^2 \) were cleaved from the wafers and introduced into the ultrahigh vacuum (UHV) preparation chamber, where they were outgassed over night at \( \sim 200 \) °C to desorb water and other surface contaminants. The sample was then transferred under UHV to the metal deposition chamber, where Pd dots 0.2 mm in diameter were thermally evaporated onto the SiO\(_2\) through a shadow mask. The substrate was held near 30 K during deposition in order to smooth the surface morphology of the thin (\( \sim 5 \) nm) Pd films. This process produced films with a nodular structure, typically, 8 nm in diameter that protruded \(< 2 \) nm above the valleys.\(^{17} \) A smooth surface morphology is desirable to reduce BEEM image contrast arising from the surface topography of the metal.\(^{14} \) The finished sample was allowed to warm up to room temperature and was then transferred under UHV into the STM chamber. The grounding contact was carefully positioned onto a selected Pd dot by means of three orthogonally mounted Inchworms\textsuperscript{TM}. STM images and sets of BEEM spectra were then taken. Typically, 9–25 BEEM spectra were measured in a grid pattern covering 25×25 to 50×50 nm\(^2 \) areas. As will become apparent in the next section, it is desirable to widely separate the acquisition points for each spectrum to avoid charging effects arising from electrons in-
SiO$_2$ layer, which arise from the constructive/destructive interference is attributed to quantum interference effects in the thin collector current that progressively broadens and weakens. In the simplest realization, transmission maxima follow the quantization condition: $E = (n \pi h/d)^2/2m^*$ ($n = 1, 2, 3, ...$), where $E$ is the electron energy, $d$ the cavity width, and $m^*$ the effective electron mass. No oscillatory structure due to the metallic film was ever observed by us, a failure that we attribute to the uneven nodular character of the Pd film. The oscillatory structure in the first scan of Fig. 2 is repeatable provided the scan is made on a new, previously unexposed point of the sample. However, only about 1/3 of the virgin points yielded a spectral structure with similar periodicities; the remainder lacked the oscillatory structure entirely or exhibited a weak and smeared out structure of varying periodicities. After a number of scans, shown here at the ninth, the structure is altered and strongly suppressed. A second point to be noted is the progressive increase in the collector current with each scan. Such increases were previously observed, and were attributed to the buildup of stress-induced positive charge near the anode (OS interface). Although for thicker oxides ($d > 4$ nm) electrons are trapped in the oxide, resulting in an increase in $V_o$ and a decrease $I_c$, for thinner oxides the electrons leak out, thereby revealing the presence of the positive charge. Its presence at the anode has a small effect ($<0.1$ V) on $V_o$, primarily due to image force lowering, that is consistent with our observations ($\sim 0.05$ V). Yet, the positive charge creates an accelerating field that, again with the inclusion of image force effects, results in an enhancement of transmission probabilities and an increase in $I_c$. Since the positive charge is randomly distributed, its buildup during the scans progressively distorts the local potential the electrons see as they traverse the oxide. Such potential fluctuations affect the ability of the electron waves to interfere coherently.

The oscillatory structure commonly observed on a virgin portion of the surface, such as the bottom curve in Fig. 2, exhibits peaks for $V_T = 4.6, 5.1, 5.8$, and 6.8 V. We have limited ourselves to $V_T < 7$ V to minimize hot electron damage. We also convinced ourselves that an additional weak peak appears near 4.1 V, but is not readily discernible in an average spectrum because of the background noise. It should be realized that less than 1 in 1000 electrons injected by the STM tip are collected in the Si substrate. The oscillatory structure is also shown in Fig. 3, where we have averaged spectra from five data sets. The observation of pronounced oscillation due to quantum interference effects is at first somewhat surprising, since the "cavity" of the SiO$_2$ film is quite leaky, with allowed states in both cladding regions (metal and Si) expected to reduce the reflectivity at the interfaces. Moreover, the extensive electron–phonon scattering in SiO$_2$, with a mean-free path of 1–2 nm that is, typically, less than the SiO$_2$ film thickness, is expected to further suppress the interference oscillations. Of course, interference oscillations have been observed, albeit weak, in MOS capacitors using the FN injection method. Support for the correctness of this interpretation also comes from the theoretical modeling that will be described next. Compared to the early work by Gundlach for over the barrier interference, the present work incorporates image force effects, which

**Fig. 2.** Single scan BEEM spectra on a 5 nm Pd/2.8 nm SiO$_2$/n-Si(100) MOS structure measured at the same point on the sample. The numerals indicate the number of the scan. The first spectrum was taken on a previously unexposed area of the sample. $V_o$ marks the current threshold bias, obtained by computer-aided fits. The spectra are vertically displaced for clarity. $I_T = 2$ nA, $V_s = 0$ V.
represent the screening of the electrons in SiO₂ by nearby conduction electrons in the metal and Si. We will fit the theoretical curves to our data and extract from it the relevant parameter of the effective conduction-band mass \( m_{ox} \) of SiO₂.

**IV. THEORETICAL TRANSMISSION COEFFICIENTS**

The transmission coefficient (TC) \( T(E) \) was calculated by a numerical solution of the one-dimensional Schrödinger equation assuming an idealized potential barrier with (i) the classical image potential, (ii) its divergencies removed as discussed below, (iii) neglecting oxide charges, and (iv) using the optical dielectric constant of the present thin SiO₂ layer. For dispersion in the latter, we assumed a parabolic \( E(k) \) relation with an effective mass \( m_{ox} \) as parameter. The barrier was discretized by \( N \) partial subbarriers of rectangular shape which covered the whole oxide layer of thickness \( d \).

From the continuity of wave-function and quantum-mechanical current density at each boundary, the TC is then found by (see, e.g., Ref. 24)

\[
T(E) = \frac{m_0}{m_{N+1}} |\text{det} M|^{2} \frac{k_{N+1}}{k_{0}} |M_{22}|^{-2},
\]

where \( M \) is a (2×2) product matrix \( M = \Pi_{j=0}^{N} M_{j} \) with transfer matrices \( M_{j} \) given by

\[
M_{j} = \frac{1}{2} \begin{pmatrix}
(1+S_{j})\exp[-i(k_{j+1}-k_{j})x_{j}] & (1-S_{j})\exp[-i(k_{j+1}+k_{j})x_{j}]
\end{pmatrix}\begin{pmatrix}
(1-S_{j})\exp[i(k_{j+1}+k_{j})x_{j}] & (1+S_{j})\exp[i(k_{j+1}-k_{j})x_{j}]
\end{pmatrix}.
\]

In Eq. (2) \( S_{j} = m_{j+1}/m_{j} \), and the effective masses and momenta are discretized as \( m_{j} = m_{0}\varepsilon_{j} [(x_{j-1}+x_{j})/2] \) and \( k_{j} = [k(x_{j-1}+x_{j})/2] \), respectively, \( x_{j} \) being the position of the \( j \)th boundary. If the metal–oxide interface is at \( x_{0} \) and the oxide–silicon interface at \( x_{N} \), then \( m_{ox} = m_{M} \) denotes an effective mass in the metal electrode and \( m_{Si} = m_{Si} \) an ‘effective’ mass in silicon. For all other \( l \) we have \( m_{l} = m_{ox} \). Because of the assumed parabolic dispersion within the oxide, the momentum takes the form

\[
k(x) = \sqrt{2m_{ox}/\hbar^{2}} \sqrt{E - [\Phi_{B} + eF_{ox}x + E_{im}(x)]},
\]

there, with the image potential

\[
E_{im}(x) = -\frac{e^{2}}{16\pi\varepsilon_{ox}} \sum_{n=0}^{\infty} (-\kappa)^{n} \left[ \frac{1}{nd+x} + \frac{\kappa}{d(n+1)-x} + \frac{2\kappa}{d(n+1)} \right],
\]

which includes the effect of all images in the two electrodes. In Eq. (4) \( \kappa \) is given by \( \kappa = (\varepsilon_{ox} - \varepsilon_{Si})/(\varepsilon_{ox} + \varepsilon_{Si}) \). The remaining quantities are the metal–SiO₂ barrier height for electrons \( \Phi_{B} \), the built-in potential drop over the oxide layer \( eF_{ox}x \), and the dielectric constants \( \varepsilon_{ox} \) and \( \varepsilon_{Si} \) in oxide and silicon, respectively. Neglecting the image force, \( T(E) \) can be written analytically in terms of Airy functions as was first done by Gundlach. In our simulations we used the following parameters: \( d = 2.8 \text{ nm}, N = 30, \Phi_{B} = 4.1 \text{ eV}, F_{ox} = V_{ox}/d = -0.071 \text{ 43 V/nm} \) (potential peak at the oxide–metal boundary), \( m_{Si} = 0.19m_{o} \), \( F_{ox} = 2.13 \).

The significance of the ‘classical’ image force in tunneling experiments was supported by Binnig et al. They showed that it is indispensable in order to describe correctly the barrier-width dependence and absolute value of the vacuum tunnel current. The existence of image force effects for over the barrier transport in MOS structures was also shown recently by Wen et al. On the other hand, the ‘classical’ form can only be used asymptotically, i.e., a few Bohrs off the image plane. In the vicinity of that plane, the classical singularity has to be replaced by a self-consistent potential shape. This shape is smooth throughout the interface and can be modeled by a smooth variation of the dielectric constant. For simplicity, we have removed the singularity of the classical image potential in a more simplistic way by a straight continuation of both, the band edge in the semiconductor and the gate Fermi level.

The simulations involve further simplifications. Any possible band-structure mismatch at the Si–SiO₂ interface was disregarded. In above-barrier transitions electrons tunnel into highly excited states in the silicon near the Si–SiO₂ boundary. Here, the ‘effective’ mass \( m_{Si} \) is merely a fitting parameter. Fortunately, \( m_{Si} \) only enters the exponential factor of the TC and has no significant influence on the
theory, based on thicker oxides, for the image force lower-
experimental observations and predictions of image force
threshold is closer to 3.9 eV. The decrease is consistent with
Monte Carlo calculations. However, the role of transport
ion due to the complexity of the transmission process of hot
should be simulated. Neither is, at present, a realizable op-
mental data either a corresponding function should be de-
V. DISCUSSION AND CONCLUSIONS
increased intensity of the tail in
creasing the cavity width
ity. Hence, the periodicity increases, as it also would by de-
for good reason, as much of this information is neither avail-
able, nor calculable within the framework of present knowl-
the structurally incoherent system that the MOS
structure represents.
As BEEM spectra in general exhibit little structure and obey,
at least near threshold, a power-law dependence of the
collector current \( I_c \) on \( V_T \). we can attempt to represent the
BEEM spectra by multiplying the transmission coefficient
with a simple quadratic power law, i.e., \( I_c \propto (V_T - V_o)^2 \). The
result is shown for \( V_o = 3.9 \) V and \( T(E) \) calculated with \( m_{ox} = 0.63 m_o \) and with image forces included in Fig. 3 as a
solid line. As can be ascertained, an energy-independent
\( m_{ox} \approx 0.63 m_o \) is sufficient for a reasonable fit over the entire
voltage range. No attempt has been made to make the curves
overlap, but merely to show the position of the structure. The
sensitivity of the structure on \( m_{ox} \) (aside from that shown in
Fig. 4) can be estimated from differentiating the quantization
condition \( E = (n \pi h/d)^2/2m^* \). Thus, \( \Delta m_{ox} \approx -\frac{\delta E}{E} m_{ox} \),
with a change in the peak location, let us say near 6 eV, of
0.1 eV resulting in a \( \Delta m_{ox} = 0.01 m_o \). Thus, a conservative
estimate of the error gives a best-fit value of \( m_{ox} = 0.63 \pm 0.02 m_o \). In contrast, the error in \( d \) of \( \pm 0.2 \) nm yields a
substantially larger uncertainty of \( \pm 0.09 m_o \). Other uncer-
tainties due to a lack of knowledge in \( V_{ox} \) (\( \pm 0.1 \) V) or
choice of \( \epsilon_{ox} \) give uncertainties of \( \pm 0.01 m_o \), so that our
present best estimate for \( m_{ox} \) is \( m_{ox} = 0.63 \pm 0.09 m_o \).
Also shown in Fig. 3 is the dashed curve generated with a
\( T(E) \) calculated with a trapezoidal barrier, i.e., with the omis-
sion of image force effects, but otherwise with identical pa-
rameters as the solid curve. The latter clearly gives a better
fit to the data. Ignoring image force effects and optimizing
the fit to the experimental data yield a \( m_{ox} = 0.65 m_o \). How-
ever, we find no physical reason to ignore image force ef-ects, but merely show its role, having been motivated to
show it by reason of a consistent historical neglect of image
force effects by most practitioners of the art of electrical
characterization of MOS structures.

The consequence of omission of image force effects is
rather small on the magnitude of \( m_{ox} \), however, its inclusion
has a dramatic effect on the transmission coefficient in the
presence of an oxide field. This is illustrated for relatively
moderate fields in Fig. 5. The lowering of the threshold for
increasing \( V_{ox} \) is clearly observable, with an accompanying
expansion of the period for low \( n \) values (i.e., initial period-
licity for \( V_{ox} = 0 \) is less than that for \( V_{ox} > 0 \)). It is interesting
to note that for \( V_{ox} = 1 \) V the weak first peak corresponds to
electrons partially tunneling through the top of the barrier
before interference occurs (somewhat akin to the FN case).
The rapid shifting of the structure for even moderate fields
clearly suggests that in the presence of field inhomogeneities
on the local sampling scale the observation of the interfer-
ence effect would be quickly suppressed. In our experiment,
positive charge near the anode is (randomly) generated, a
conclusion also reached from other stressing experiments
\( (I-V) \) on MOS capacitor structures. Even a single charge
would generate a field of order 1 V/nm at the injecting point
of the SiO\(_2\) layer. Even at a distance of several nanometers

![Image force included](image-url)

**Fig. 4.** Calculated transmission coefficients, image force effects included, for \( m_{ox} = 0.63 m_o \) (solid line) and \( m_{ox} = 0.42 m_o \) (dashed line), with the remain-
ing parameters determined from experiment. The solid line was used to
determine the best fit in Fig. 3.

interpretation of the measurements. The missing knowledge
about the band structure of the ultrathin SiO\(_2\) layer is covered
by the “tunneling” mass \( m_{ox} \). This parameter can be ad-
justed when the oscillations of the simulated TC are brought
in coincidence with the periodicity of the measured current.

Results of the calculation for the selected parameters are
shown in Fig. 4 (solid line). The transmission coefficient
\( T(E) \) exhibits initially a strong oscillatory structure whose
period increases and whose amplitude decreases with energy.
Although a barrier of \( \Phi_B = 4.1 \) eV was used, the transmission
threshold is closer to 3.9 eV. The decrease is consistent with
experimental observations and predictions of image force
theory, based on thicker oxides, for the image force lower-
experimental observations and predictions of image force
threshold is closer to 3.9 eV. The decrease is consistent with
Monte Carlo calculations. However, the role of transport
ion due to the complexity of the transmission process of hot
should be simulated. Neither is, at present, a realizable op-
mental data either a corresponding function should be de-
V. DISCUSSION AND CONCLUSIONS
increased intensity of the tail in
creasing the cavity width
ity. Hence, the periodicity increases, as it also would by de-
for good reason, as much of this information is neither avail-
able, nor calculable within the framework of present knowl-
the structurally incoherent system that the MOS
structure represents.
As BEEM spectra in general exhibit little structure and obey,
at least near threshold, a power-law dependence of the
collector current \( I_c \) on \( V_T \). we can attempt to represent the
BEEM spectra by multiplying the transmission coefficient
with a simple quadratic power law, i.e., \( I_c \propto (V_T - V_o)^2 \). The
result is shown for \( V_o = 3.9 \) V and \( T(E) \) calculated with \( m_{ox} = 0.63 m_o \) and with image forces included in Fig. 3 as a
solid line. As can be ascertained, an energy-independent
\( m_{ox} \approx 0.63 m_o \) is sufficient for a reasonable fit over the entire
voltage range. No attempt has been made to make the curves
overlap, but merely to show the position of the structure. The
sensitivity of the structure on \( m_{ox} \) (aside from that shown in
Fig. 4) can be estimated from differentiating the quantization
condition \( E = (n \pi h/d)^2/2m^* \). Thus, \( \Delta m_{ox} \approx -\frac{\delta E}{E} m_{ox} \),
with a change in the peak location, let us say near 6 eV, of
0.1 eV resulting in a \( \Delta m_{ox} = 0.01 m_o \). Thus, a conservative
estimate of the error gives a best-fit value of \( m_{ox} = 0.63 \pm 0.02 m_o \). In contrast, the error in \( d \) of \( \pm 0.2 \) nm yields a
substantially larger uncertainty of \( \pm 0.09 m_o \). Other uncer-
tainties due to a lack of knowledge in \( V_{ox} \) (\( \pm 0.1 \) V) or
choice of \( \epsilon_{ox} \) give uncertainties of \( \pm 0.01 m_o \), so that our
present best estimate for \( m_{ox} \) is \( m_{ox} = 0.63 \pm 0.09 m_o \).
Also shown in Fig. 3 is the dashed curve generated with a
\( T(E) \) calculated with a trapezoidal barrier, i.e., with the omis-
sion of image force effects, but otherwise with identical pa-
rameters as the solid curve. The latter clearly gives a better
fit to the data. Ignoring image force effects and optimizing
the fit to the experimental data yield a \( m_{ox} = 0.65 m_o \). How-
ever, we find no physical reason to ignore image force ef-ects, but merely show its role, having been motivated to
show it by reason of a consistent historical neglect of image
force effects by most practitioners of the art of electrical
characterization of MOS structures.

The consequence of omission of image force effects is
rather small on the magnitude of \( m_{ox} \), however, its inclusion
has a dramatic effect on the transmission coefficient in the
presence of an oxide field. This is illustrated for relatively
moderate fields in Fig. 5. The lowering of the threshold for
increasing \( V_{ox} \) is clearly observable, with an accompanying
expansion of the period for low \( n \) values (i.e., initial period-
licity for \( V_{ox} = 0 \) is less than that for \( V_{ox} > 0 \)). It is interesting
to note that for \( V_{ox} = 1 \) V the weak first peak corresponds to
electrons partially tunneling through the top of the barrier
before interference occurs (somewhat akin to the FN case).
The rapid shifting of the structure for even moderate fields
clearly suggests that in the presence of field inhomogeneities
on the local sampling scale the observation of the interfer-
ence effect would be quickly suppressed. In our experiment,
positive charge near the anode is (randomly) generated, a
conclusion also reached from other stressing experiments
\( (I-V) \) on MOS capacitor structures. Even a single charge
would generate a field of order 1 V/nm at the injecting point
of the SiO\(_2\) layer. Even at a distance of several nanometers
away the resulting fields are comparable or larger than those
in the simulations of Fig. 5. Because of scattering at the
interfaces and in the SiO₂, electrons will experience some-
what different paths. Consequently, electrons injected locally
near an area of charge would experience both a local- and
time-dependent variation of the fields, which leads to a sup-
pression of the interference effects, as was observed in our
time-dependent experiments (Fig. 2). Thus, a condition for
the observation of quantum interference is a region essen-
tially free of oxide charge. The lateral extent of this region
can only be guestimated from our observation that we
needed to move at least 10 nm away from any point of prior
exposure (and hence, positive charge buildup) before we
could observe a new oscillatory structure in the BEEM spec-
trum. The fact that a virgin area did not necessarily lead to
the observation of quantum interference suggests that the
presence of local charge was quite pervasive. Since device
quality oxides have generally quite low densities of defects,
traps, etc. (~10¹¹/cm²), it appears somewhat surprising that
we do not observe quantum interference most of the time.
Two reasons for this failure may be sited: (a) Pd metalliza-
tion induces a large (~10¹²/cm²) density of electron traps, 17
and (b) multiple scattering in the metal and SiO₂ layer can
effectively broaden the sampling area. Although no net elec-
tron charge has been observed in the thin layers used here,
electrons can nevertheless momentarily be trapped before
leaking out by tunneling to the electrodes. 21 A trapped elec-
tron acts as a scattering center and distorts the field sensed by
the other electrons passing in its vicinity.

We have shown here that direct electron injection into a
laterally confined area of a MOS structure can lead to the
observation of strong quantum interference oscillations. A
theoretical analysis yields an effective conduction-band mass
of 0.63m₀, and further reveals an extreme sensitivity of the
oscillatory structure to the oxide thickness and the oxide
field. The technique has, thus, the potential of an extremely
sensitive local probe to address issues of local structural and
electric homogeneity, issues of great importance in the area
of future ultrasmall devices. It is to be expected that the use
of polygates with their drastically lower density of trap states
would considerably enhance the observation of quantum in-
terference in thin oxides, and thereby facilitate the realization
of this technique as a potentially powerful local probe to
assess dielectric quality.


\(^{15}\) A 15, 784 (1997).


\(^{17}\) R. Ludeke, E. Cartier, and H. J. Wen (unpublished results). The transmis-
sion probability here is the one associated with inelastic scattering events
due to electron–phonon interactions, see Ref. 14 for further details.

\(^{18}\) E. Cartier, D. Arnold, D. J. DiMaria, M. V. Fischetti, P. Braunlich, S. C.
Jones, X. A. Shen, R. T. Casper, and P. J. Kelly, Rev. Solid State Sci. 5,


\(^{24}\) W. J. Kaiser and L. D. Bell, Phys. Rev. Lett. 60, 1406 (1988); L. D. Bell

Lett. 65, 1820 (1994).