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Consequences of valley filtering on abrupt junction AlGaAs/GaAs heterojunction bipolar transistors

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Electron transport in AlGaAs/GaAs heterojunction bipolar transistors with compositionally abrupt emitter-base junctions is examined. Transport across the abrupt emitter-base heterojunction is treated quantum mechanically, and the Monte Carlo technique is used to study transport through the base. Although there is a sizeable population of upper-valley electrons in the bulk emitter, the AlGaAs/GaAs heterojunction is found to favor the injection of Γ-valley electrons into the base. This valley filtering effect enhances device performance by reducing base transit time, but quantum mechanical tunneling lowers the average energy of the injected flux which increases base transit time. The design of a heterojunction bipolar transistor for minimum base transit time involves a careful tradeoff between these competing factors. We examine the influence of varying aluminum fraction and bias on base transit time. The results suggest that a moderately doped emitter with high aluminum mole fraction produces the shortest base transit time.

I. INTRODUCTION

The emitter-base junction of a heterojunction bipolar transistor (HBT) may be either compositionally abrupt or graded. Because grading of the emitter-base heterojunction increases electron injection, compositional grading is commonly used to ensure high common emitter current gain and low turn-on voltage.[1–3] On the other hand, the abrupt emitter-base heterojunction provides a launching ramp for electrons injected into the base which is expected to improve both the base transit time[4] and base transport factor.[5] Recent experimental[5] and theoretical studies[6] have shown that abrupt-junction HBTs may display higher common emitter current gains (β) than graded-junction HBTs when the current gain is limited by the base transport factor (α_t) instead of emitter injection efficiency (γ).[7] To ensure high common emitter current gain and high-speed operation, the design of the emitter and base of an abrupt-junction HBT should be optimized to reduce the average base transit time.

For a uniform-base HBT, the base transit time primarily depends on the nature of the injected electron flux and on the type of scattering carriers undergo during their passage through the base. If upper-valley electrons are present in the injected flux, they will increase the number of intervalley scattering events. For Γ-valley electrons, electron-plasmon scattering dominates in the heavily doped bases typically employed for HBTs.[8] Issues concerning the design of the base and its impact on the base transit time have been studied by previous researchers.[8,9] We focus, instead, on the influence of injected electron flux on base transit time.

This paper was motivated by the recent work of Ramberg and Ishibashi[10] who suggested that the base transit time could be improved by filtering out the upper-valley electrons present in the emitter before they are injected into the base. Previous Monte Carlo studies had demonstrated that a small percentage of upper-valley electrons in the injected flux could significantly degrade the steady-state base transit time.[11] The filtering effect was to be achieved by properly designing the abrupt emitter-base heterojunction in order to enhance tunneling of Γ-valley electrons through the conduction-band spike. Since the Γ-valley electrons are lighter than those in the L or X valley, they have a higher probability of quantum mechanically tunneling through the conduction-band spike and, as a result, the electron flux incident on the base should be rich in Γ-valley electrons.

We find that the valley filtering effect is due to two distinct mechanisms. First, the different band offsets for the Γ, X, and L valleys produce different barrier heights for electrons in these valleys which naturally lead to a filtering effect. Consider the energy-band diagram for a typical emitter-base heterojunction as displayed in Fig. 1(a) (a conduction-band discontinuity of 65% was assumed for the Γ valley[12]). This figure shows that the barrier for Γ-valley electrons, $V_{b\Gamma}$ is much smaller than that for the X valley, V_{bX}. The flux of electrons injected into the base should be correspondingly rich in Γ-valley electrons. The strong tunneling of Γ-valley electrons further reduces their effective barrier height and additionally improves the filtering effect.

The second mechanism for valley filtering is illustrated by the energy-band diagram for Γ and L valleys which is displayed in Fig. 1(b). The barrier heights for Γ- and L-valley electrons are nearly equal ($V_{b\Gamma} \simeq V_{bL}$), but the strong tunneling of the light, Γ-valley electrons reduces the effective barrier for Γ-valley electrons and produces a filtering effect. This is effective mass filtering as described by Ramberg and Ishibashi.[10] We should stress that tunneling which enhances filtering in the first case and is responsible for filtering in the second case, also lowers the average energy of injected Γ-valley electrons. The design of abrupt emitter-base heterojunction involves a careful tradeoff; enhanced tunneling improves filtering but reduces the effectiveness of the heterojunction launching ramp. The purpose of this paper is to examine this tradeoff quantitatively.

The paper is organized into three sections. In the next section, the simulation techniques are described briefly. In

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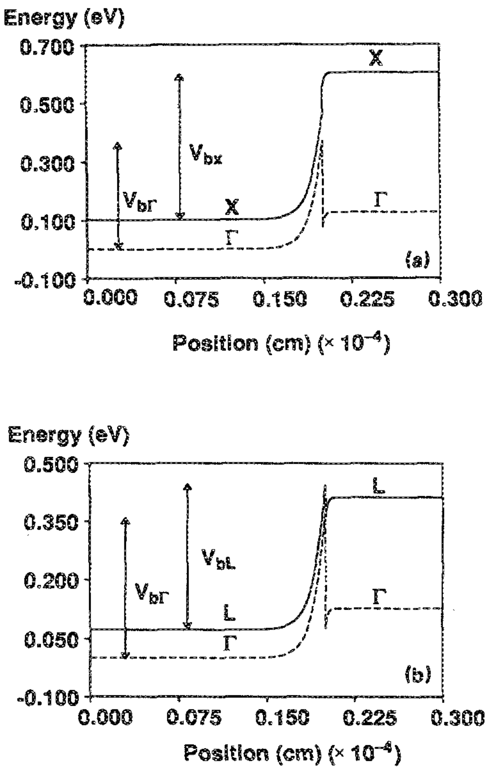

FIG. 1. (a) The band diagrams of the Γ and X valley of an abrupt AlGaAs/GaAs Np heterojunction. The emitter doping is $1.0 \times 10^{18}/\text{cm}^3$. Bias is fixed at 1.2 V. The relevant material parameters are listed in Table I. (b) The band diagrams of the Γ and L valley of an abrupt AlGaAs/GaAs Np heterojunction. The emitter doping is $1.0 \times 10^{18}/\text{cm}^3$. Bias is fixed at 1.2 V. The relevant material parameters are listed in Table I.

Sec. III, we describe and discuss the results of simulations of various HBT structures. Finally, the paper ends by summarizing the tradeoffs involved in designing the emitter-base junction to minimize base transit time.

II. THE SIMULATION APPROACH

To estimate the base transit time, both carrier injection across the emitter-base heterointerface and carrier transport across the quasi-neutral base have to be considered. Electron transport across the heterointerface determines both the energy distribution of carriers injected into the base and the composition of the electron flux (the percentage of electrons in different valleys). In the $Al_xGa_{1-x}As$ emitter (with x typically about 0.3), a significant population of upper-valley electrons exists. We measure the extent of valley filtering in terms of the flux ratio which we define as the ratio of the Γ-valley electron flux to the total electron flux in Γ, L, and X valleys. Once the energy distribution of the injected electron flux is found, the transport of those carriers through the quasi-neutral base is simulated to estimate the average base transit time.

Electron injection (from Γ, L, and X valleys of the AlGaAs emitter to the respective Γ, L, and X valleys of the GaAs base) across the abrupt emitter-base heterojunction is treated quantum mechanically by numerically solving Schroedinger's equation across the heterojunction as described in Ref. 6. All three valleys were included because high mole fraction $Al_xGa_{1-x}As$ emitters contain significant proportion of Γ-, L-, and X-valley electrons. The energy-band profile for each of the three valleys was first obtained from a conventional numerical simulation program.[13] Across the heterojunction, a Γ- valley discontinuity of 65% of the Γ-valley band-gap difference was assumed.[12] From the resulting conduction-band profiles, such as those showed in Figs. 1(a) and 1(b), we then computed electron current injected into the base by assuming that the emitter contact launched electron waves which propagated without scattering through the structure. Since the probability of elastic tunneling from one valley to another across a heterojunction is small,[14,15] we treated the process of electron injection across the heterojunction separately for the Γ, L, and X valleys. It is possible for electrons to tunnel inelastically between valleys, but inelastic tunneling appears to be minimal for the very thin barriers ($\lesssim 20$ Å) encountered in this work.[16]

After computing the electron flux injected into the base, Monte Carlo simulation[17,18] was used to study the steady-state transport of electrons across the base. The initial carrier was selected by rejection techniques from the quantum mechanically computed incident electron flux. The electron trajectories were then followed as they traversed the base under the influence of the scattering potentials. The treatment of minority-carrier electrons scattering in p^+-GaAs within a Monte Carlo simulation is a difficult problem. Results have very recently been reported, but a number of uncertainties remain.[19] For our work, we applied a simple approach, which Katoh, Kurata, and Yoshida have successfully employed for HBT simulation.[8] This approach, briefly described below, should serve well to illustrate the nature of the design tradeoffs involved.

In addition to the standard scattering mechanisms for the AlGaAs/GaAs system, we also treated electron-plasmon scattering and we statically screened polar optical phonon (POP) scattering. Scattering of electrons by hole plasmons was calculated after[20] with a cutoff wave vector taken to be the half of inverse of Debye length.[21] Overlap factors and corrections due to nonparabolicity were taken into account appropriately. Following Ref. 8, we neglected the coupling between hole plasmons and polar optical phonons. Such coupling is important when the plasmon and longitudinal optical phonon frequencies are comparable. For the heavy base doping employed ($\sim 10^{19}$ cm^{-3}), it is not unreasonable to neglect the coupling.[8]

Figure 1 of Ref. 8 shows that plasmon scattering dominates for minority-carrier, Γ-valley electrons. The importance of POP scattering is greatly diminished by static screening by the hole plasma.[8] In addition to treating electron-plasmon scattering, we also treated binary, electron-heavy hole scattering. The heavy holes were assumed to be fixed in position and were treated much like the ionized impurities.[22] Strictly speaking, electron-hole scattering is not purely elastic in nature and energy transfer from electrons to the hole system due to intra- and intervalence-band transitions should be taken into account.[19,23] Given the dominance

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TABLE I. The details of the HBT structure used in the simulation.

	Layer	Thickness (Å)	Doping (cm^{-3})
Emitter	N $Al_{0.35}Ga_{0.65}As$	2000	···
Base	p GaAs	500	1.0×10^{19}
Collector	n GaAs	3000	1.0×10^{17}

of electron-plasmon scattering, a rigorous treatment of this problem was not warranted.

III. SIMULATION RESULTS AND DISCUSSION

Details of the HBT structures that were simulated are displayed in Table I. Simulations were conducted with emitter dopings of 1.0×10^{17} and 1.0×10^{18} cm^{-3} at an emitter-base bias of 1.2 V. We begin by discussing the injection of electrons across the emitter-base heterojunction.

Figures 2(a) and 2(b) are plots of the flux of Γ-valley electrons injected into the base versus energy of the electrons for two different emitter dopings. The height of the conduction-band spike ΔE_C is 0.283 eV. In both cases, the average energy of the injected carriers is substantially lower than the height of the conduction-band spike, ΔE_C, which illustrates the importance of tunneling. For the highly doped emitter, the average energy of the injected Γ-valley electrons is about 0.1 eV, whereas for the lightly doped emitter it is about 0.25 eV. This difference is a simple consequence of the fact that the barrier is narrower for the highly doped emitter, so tunneling is enhanced. On the other hand, enhanced tunneling produces an injected flux that is richer in Γ-valley electrons which is beneficial for base transport.

Figure 3(a) displays the variation of flux ratio with aluminum mole fraction in $Al_xGa_{1-x}As$ emitter. The flux of upper-valley electrons in the emitter can be neglected only for emitter mole fractions of less than about 0.2. For increasing mole fractions, an increasing portion of the flux is carried

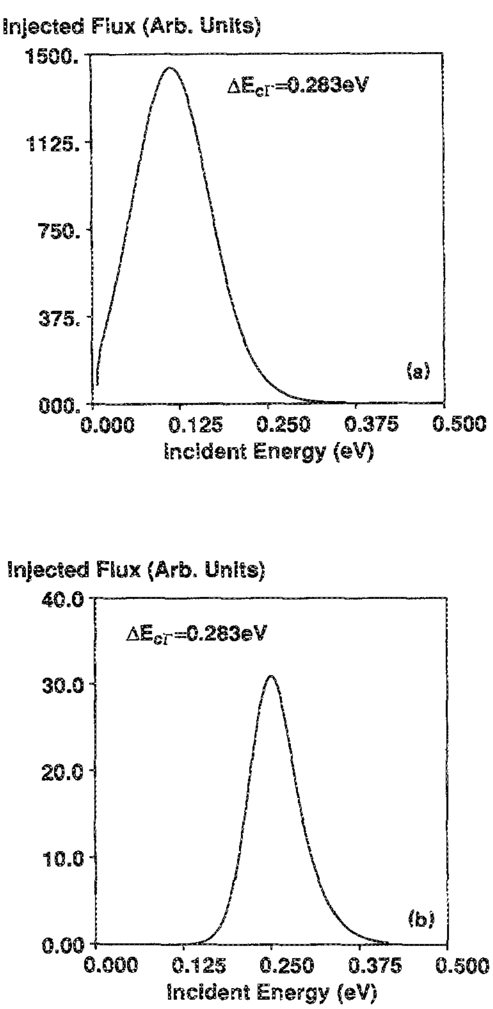

FIG. 2. (a) Injected flux into the base from the emitter vs incident energy with emitter doped at $1.0\times10^{18}/cm^3$. (b) Injected flux into the base from the emitter vs incident energy with emitter doped at $1.0\times10^{17}/cm^3$.

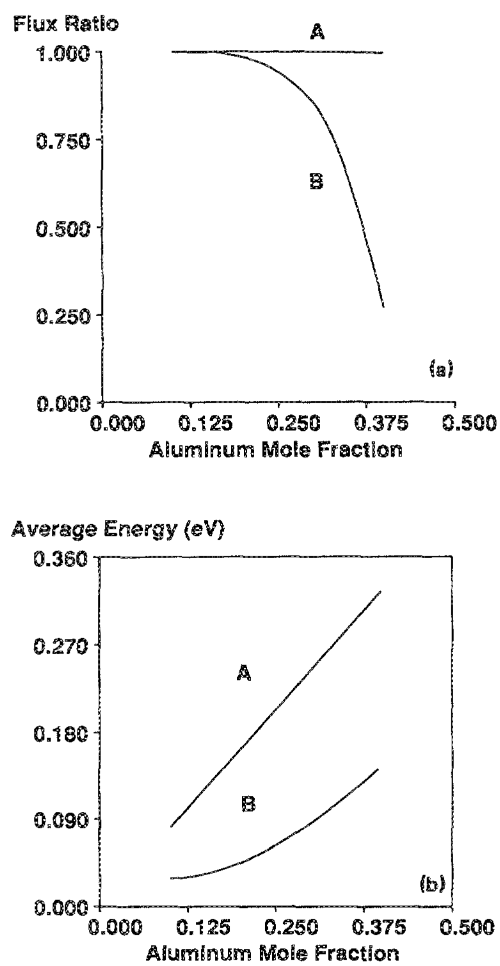

FIG. 3. (a) Dependence of flux ratio on the aluminum mole fraction of the AlGaAs emitter. A: injected flux; B: bulk emitter flux. The GaAs base is doped p type at $1.0\times10^{19}/cm^3$. The AlGaAs emitter is doped n type at $1.0\times10^{18}/cm^3$. (b) A: $\Delta E_{C\Gamma}$ vs aluminum mole fraction in the emitter. B: Dependence of average energy of the electrons injected into the base from the emitter on the aluminum mole fraction of the emitter. GaAs base is doped p type at $1.0\times10^{19}/cm^3$. The AlGaAs emitter is doped n type at $1.0\times10^{18}/cm^3$.

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by upper-valley electrons [see curve B in Fig. 3(a)]. If these upper-valley electrons were to be injected into the base, they would scatter rapidly and degrade the base transit time.[11] Figure 3(a) shows, however, that as a consequence of the band offsets and of the enhanced tunneling of Γ-valley electrons, the electron flux injected into the base (curve A) is essentially without upper-valley electrons. Therefore, despite the sizeable fraction of upper-valley electrons in the emitter for high AlAs mole fractions, the flux injected into the base is comprised mostly of Γ-valley electrons. As displayed in Fig. 3(b), a high mole fraction in the emitter is beneficial because it increases the average energy of injection. Note, however, the strong influence of tunneling, which greatly reduces the effective height of the launching ramp.

Next we examine valley filtering as a function of emitter-base forward bias. Because the barrier widens with forward bias, the importance of tunneling decreases. The reduced tunneling current for the Γ-valley electrons degrades the flux ratio after the junction. In Figs. 4(a) and 4(b), we plot the flux ratio versus emitter-base bias for two different emitter dopings. For a highly doped emitter, the decrease in the flux ratio with bias is negligible, but for a lightly doped emitter the flux ratio is observed to degrade considerably with bias. The difference in the behavior with bias can be explained by examining Fig. 4(c), which shows the ratio of the thermionic emission component to the total current for the two HBTs. For the lightly doped emitter, the tunneling current, which provides the filtering effect, decreases more rapidly with bias which decreases the population of Γ-valley electrons at high bias.

To illustrate the effects of upper-valley electron injection on base transit time, we conducted several Monte Carlo simulations. First, the electron flux from an emitter doped at 1.0×10^{18} cm^{-3} was injected into a 500-Å-wide base, doped 1.0×10^{19} cm^{-3}. The flux distribution was that found by the quantum mechanical treatment described earlier. Next, we injected an unfiltered electron flux (the proportion of upper-valley electrons in the flux was exactly the same as it was in the bulk emitter) from an energy ramp whose height was equal to the average longitudinal energy of the quantum mechanically computed flux. The results of these simulations are presented in Table II, in rows 1 and 2. The steady-state base transit time for the unfiltered flux was found to be twice that of the filtered flux. The increase in the base transit time is mainly due to an increase in the intervalley scattering rate (from 0.3% for the filtered flux to 8.5% for the unfiltered flux) which randomizes the momentum and reduces the average velocity of the carriers passing through the base. It should be understood that the above model does not represent a realistic situation, instead, it illustrates how effective mass filtering influences base transit time.

Next, we examined carrier transport across the same 500-Å-wide base but with the carriers injected from emitters with two different dopings, 1.0×10^{18} and 1.0×10^{17} cm^{-3}, at an emitter-base bias of 1.2 V. The results are displayed in Table II, rows 1 and 3, respectively. The base transit time for the lightly doped emitter is shorter than it is for the highly doped emitter. Enhanced tunneling in the heavily doped

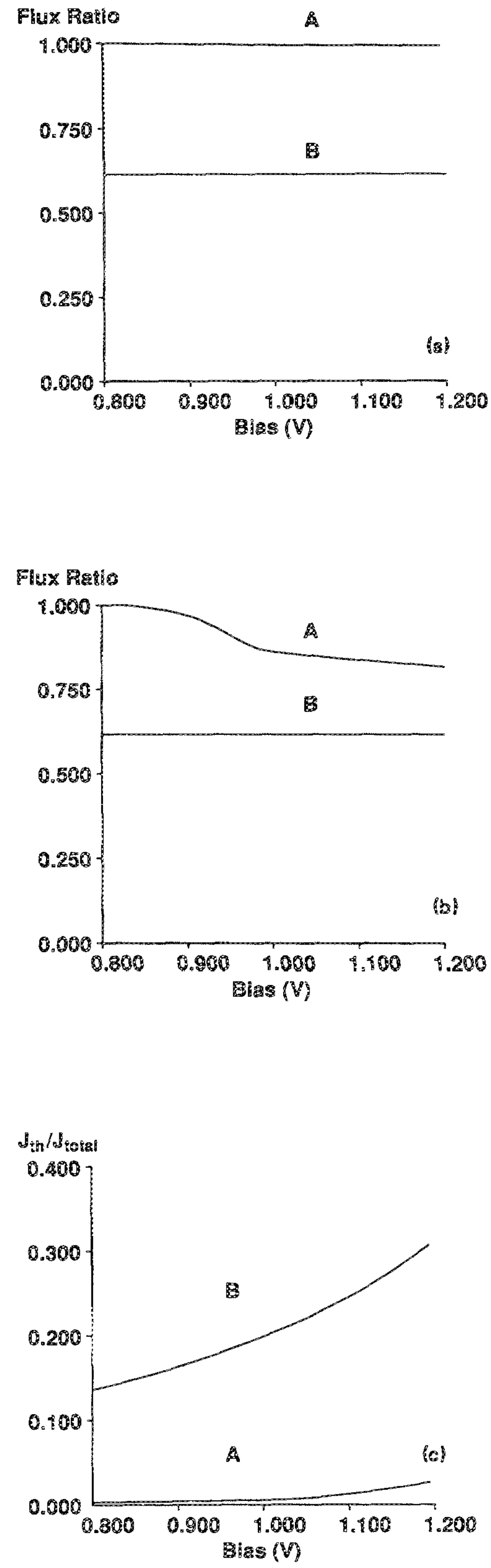

FIG. 4. (a) Dependence of flux ratio on the emitter-base bias for an aluminum mole fraction of 35% with an emitter doping of 1.0×10^{18}/cm^3. A: injected flux, B: bulk emitter flux. (b) Dependence of flux ratio on the emitter-base bias for an aluminum mole fraction of 35% with an emitter doping of 1.0×10^{17}/cm^3. A: injected flux, B: bulk emitter flux. (c) The proportion of thermionic emission current in the total current across the emitter-base junction for A: an emitter doping of 1.0×10^{18}/cm^3, B: an emitter doping of 1.0×10^{17}/cm^3.

TABLE II. The details of the simulation of carrier transport in the base. The width of the p-type base is 500 Å and doping 1.0×10^{19} cm^{-3}. The aluminum fraction of the emitter is 35%. The emitter-base bias is 1.2 V. Injection energy implies average energy of the injected flux from the emitter to the base.

Simulation No.	Injection energy (meV)	Emitter doping (cm^{-3})	Filter ratio	Transit time (ps)	Intervalley scattering (%)
1	99.0	1.0×10^{18}	0.99	0.36	0.32
2	99.0	1.0×10^{18}	0.76	0.66	8.47
3	250	1.0×10^{17}	0.86	0.28	6.67

emitter provides better filtering but at the same time it reduces the average energy of injected carriers, which increases the base transit time. These results demonstrate that the reduction in the base transit time achieved by better effective mass filtering should be carefully weighed against the increase in base transit time due to the reduced energy of the injected flux.

IV. CONCLUSION

This work was concerned with examining how the heterojunction filters the electron flux injected from the emitter of an HBT into the base and with the consequences of this filtering on base transit time. Due to the different barrier heights for Γ-, L-, and X- valley electrons, filtering of injected flux at the emitter-base heterojunctions occurs even in the absence of tunneling. Tunneling additionally improves the filtering effect by allowing Γ-valley electrons to strongly tunnel to the base. Tunneling, however, reduces the average energy of the injected flux, which lowers the effectiveness of the launching ramp. We showed that it is possible to design very effective filters which inject very few upper-valley electrons into the base.

To design an emitter-base junction for minimum base transit time, however, a tradeoff must be considered. A junction designed to enhance tunneling of Γ-valley electrons will provide good effective mass filtering which is beneficial, but will also lower the average energy of the injected flux which reduces the effectiveness of the heterojunction launching ramp. The simulations demonstrated that highly doped emitters provide the best filtering, but their base transit time suffers from the low effective height of the launching ramp. A moderately doped emitter ($\sim10^{17}$ cm^{-3}) with a high mole fraction (0.3–0.4) appears to be the best compromise. The reduced emitter-base junction capacitance is another advantage for the lightly doped emitter.

The use of compositionally abrupt emitter-base heterojunctions poses manufacturing difficulties because of the need for precise control and alignment of the doping and compositional junction. One of the adantages of HBTs, their well-controlled turn-on voltage, suffers when abrupt junctions are employed.[24] Moreover, as this study demonstrates, the benefits of the launching ramp are not easy to achieve—careful design of the junction is essential. These considerations suggest that it will be difficult to achieve significant performance advantages by using compositionally abrupt emitter-base heterojunctions.

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