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On the structure of Milnor $K$-groups of certain complete discrete valuation fields


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On the structure of Milnor $K$-groups of certain complete discrete valuation fields

par Masato KURIHARA

Résumé. Pour un exemple typique de corps de valuation discrète complet $K$ de type II au sens de [12], nous déterminons les quotients gradués $\text{gr}^i K_2(K)$ pour tout $i > 0$. Dans l’appendice, nous décrivons les $K$-groupes de Milnor d’un certain anneau local à l’aide de modules de différentielles, qui sont liés à la théorie de la cohomologie syntomique.

Abstract. For a typical example of a complete discrete valuation field $K$ of type II in the sense of [12], we determine the graded quotients $\text{gr}^i K_2(K)$ for all $i > 0$. In the Appendix, we describe the Milnor $K$-groups of a certain local ring by using differential modules, which are related to the theory of syntomic cohomology.

0. Introduction

In the arithmetic of higher dimensional local fields, the Milnor $K$-theory plays an important role. For example, in local class field theory of Kato and Parshin, the Galois group of the maximal abelian extension is described by the Milnor $K$-group, and the information on the ramification is in the Milnor $K$-group, at least for abelian extensions. So it is very important to know the structure of the Milnor $K$-groups.

Let $K$ be a complete discrete valuation field, $v_K$ the normalized additive valuation of $K$, $O_K$ the ring of integers, $m_K$ the maximal ideal of $O_K$, and $F$ the residue field. For $q > 0$, the Milnor $K$-group $K^M_q(K)$ has a natural filtration $U^i K^M_q(K)$ which is by definition the subgroup generated by $\{1 + m^i_K, K^x, ..., K^x\}$ for all $i \geq 0$ (cf. §1). We are interested in the graded quotients $\text{gr}^i K^M_q(K) = U^i K^M_q(K)/U^{i+1} K^M_q(K)$. The structures of $\text{gr}^i$ were determined in Bloch [1] and Graham [5] in the case that $K$ is of equal characteristic. But in the case that $K$ is of mixed characteristics, much less is known on the structures of $\text{gr}^i K^M_q(K)$. They are determined by Bloch and Kato [2] in the range that $0 \leq i \leq e_K p/(p - 1)$ where $e_K = v_K(p)$ is the absolute ramification index. They are also determined in the case $e_K = v_K(p) = 1$ (and $p > 2$), in [14] for all $i > 0$. This result was generalized in J. Nakamura [17] to the case that $K$ is absolutely tamely
ramified (cf. also [16] where some special totally ramified case was dealt). We also remark that I. Zhukov calculated the Milnor $K$-groups of some higher dimensional local fields from a different point of view ([24]).

On the other hand, we encountered strange phenomena in [12] for certain $K$ (if $K$ is of type II in the terminology of [12]). Namely, if $K$ is of type II, for some $q$ we have $\text{gr}^i K^M_q(K) = 0$ for some $i$ (even in the case $[F : F^p] = p^{q-1}$), which never happens in the equal characteristic case. A typical example of a complete discrete valuation field of type II is $K = K_0(\sqrt[p^r]{T})$ where $K_0$ is the fraction field of the localization of $\mathbb{Z}_p[T]$ at the prime ideal $(p)$. The aim of this article is to determine all $\text{gr}^i K^M_2(K)$ for this typical example of type II (Theorem 1.1), and to give a direct consequence of the theorem on the abelian extensions (Corollary 1.3). (For the structure of the $p$-adic completion of $K^M_2(K)$, see also Corollary 1.4).

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**Notation**

For an abelian group $A$ and an integer $n$, the cokernel (resp. kernel) of the multiplication by $n$ is denoted by $A/n$ (resp. $A[n]$), and the torsion subgroup of $A$ is denoted by $A_{\text{tors}}$. For a commutative ring $R$, $R^\times$ denotes the group of the units in $R$. For a discrete valuation field $K$, the ring of integers is denoted by $O_K$, and the unit group of $O_K$ is denoted by $U_K$. For a Galois module $M$ and an integer $r \in \mathbb{Z}$, $M(r)$ means the Tate twist. We fix an odd prime number $p$ throughout this paper.

1. Statement of the result

Let $K_0$ be a complete discrete valuation field with residue field $F$. We assume that $K_0$ is of characteristic 0 and $F$ is of characteristic $p > 0$, and that $p$ is a prime element of the integer ring $O_{K_0}$ of $K_0$. We further assume that $[F : F^p] = p$ and $p$ is odd.

We denote by $\Omega^1_F$ the module of absolute Kähler differentials $\Omega^1_{F/\mathbb{Z}}$. For a positive integer $n$, we define the subgroups $B_n \Omega^1_F$ by $B_1 \Omega^1_F = dF \subset \Omega^1_F$, and $C^{-1}B_n \Omega^1_F = B_{n+1} \Omega^1_F / B_1 \Omega^1_F$ for $n > 0$ where $C^{-1}$ is the inverse Cartier operator (cf. [6] 0.2). Then $B_n \Omega^1_F$ gives an increasing filtration on $\Omega^1_F$. 


We fix a $p$-base $t$ of $F$, namely $F = F^p(t)$. (Recall that we are assuming $[F : F^p] = p$.) We take a lifting $T \in U_{K_0}$ of the $p$-base $t$ of $F$, and define $K = K_0(\sqrt[p]{T})$. This is a discrete valuation field of type II in the sense of [12].

In this article, we study the structure of $K_2(K) = K_2^M(K)$. As usual, we denote the symbol by $\{a, b\}$ (which is the class of $a \otimes b$ in $K_2(K) = K^\times \otimes K^\times / J$ where $J$ is the subgroup generated by $a \otimes (1 - a)$ for $a \in K^\times \setminus \{1\}$). We write the composition of $K_2(K)$ additively. For $i \geq 0$, we define $U^iK_2(K)$ to be the subgroup of $K_2(K)$ generated by $\{U^iK, K^\times\}$ where $U^i = 1 + m'_i$. We are interested in the graded quotients

$$gr^i K_2(K) = U^iK_2(K)/U^{i+1}K_2(K). \quad (1)$$

We also use a slightly different subgroup $U^iK_2(K)$ which is, by definition, the subgroup generated by $\{U^i_{K}, U_{K}\}$. We have

$$U^1K_2(K) = U^1K_2(K) \supset U^2K_2(K) \supset U^2K_2(K) \supset U^3K_2(K) \supset \ldots$$

It is known that $K_2(K)/U^1K_2(K) \cong F^\times \oplus K_2(F)$. Further, by Bloch and Kato [2] (cf. Remark 1.2), $gr^i K_2(K)$ is determined in the range $1 \leq i \leq p + 1$ in our case (note that $e_K = v_K(p) = p$). In this article, we prove

**Theorem 1.1.** We put $\pi = \sqrt[p]{T}$ which is a prime element of $O_K$.

1. If $i > p + 1$ and $i$ is prime to $p$, we have $gr^i K_2(K) = 0$.
2. For $i = 2p$, we have $U^{2p}K_2(K) \subset U^{2p+1}K_2(K)$, and the homomorphism $x \mapsto$ the class of $\{1 + p^n\pi \bar{x}, \pi\}$

$$F \longrightarrow gr^{2p}K_2(K)$$

($\bar{x}$ is a lifting of $x$ to $O_K$) induces an isomorphism

$$F/F^p \cong gr^{2p}K_2(K).$$

3. For $i = np$ such that $n \geq 3$, we have $U^{np}K_2(K) \subset U^{np+1}K_2(K)$, and the homomorphism $x \mapsto$ the class of $\{1 + p^n\pi \bar{x}, \pi\}$ ($\bar{x}$ is a lifting of $x$ to $O_K$) gives an isomorphism

$$F^{p^{n-2}} \cong gr^{np}K_2(K).$$

**Remark 1.2.** We recall results of Bloch and Kato [2]. Let $K$ be a complete discrete valuation field of mixed characteristics $(0, p)$ with residue field $F$, and $\pi$ be a prime element of $O_K$. The homomorphisms

$$\Omega^1_F \longrightarrow U^iK_2(K)/U^{i+1}K_2(K) \quad (2)$$

$$x \cdot dy/y \mapsto \{1 + \pi^i \bar{x}, \pi\};$$

and

$$F \longrightarrow U^iK_2(K)/U^iK_2(K) \quad (3)$$

$$x \mapsto \{1 + \pi^i \bar{x}, \pi\},$$
(\tilde{x} and \tilde{y} are liftings of \(x\) and \(y\) to \(O_K\), and the classes of the symbols do not depend on the choices) are surjective. They determined the kernels of the above homomorphisms in the range \(0 < i \leq e p/(p - 1)\) where \(e = v_K(p)\). In particular, for our \(K\), the above homomorphisms (2) and (3) induce isomorphisms

(i) \(\Omega^1_{E} \xrightarrow{\sim} \text{gr}^i K_2(K)\) for \(i = 1, 2, \ldots, p - 1, \text{and } p + 1\).

(ii) \[
\begin{align*}
F/F^p & \xrightarrow{\sim} U^pK_2(K)/U^pK_2(K), \\
\Omega^1_{E}/B_1\Omega^1_{E} & \simeq U^pK_2(K)/U^{p+1}K_2(K).
\end{align*}
\]

We also remark the surjectivity of (2) and (3) implies that \(U^iK_2(K)/U^{i+1}K_2(K)\) is generated by the image of \(\{U^i_K, T\}\), and that \(U^iK_2(K)/U^{i}K_2(K)\) is generated by the image of \(\{U^i_K, \pi\}\) in our case.

Let \(U^i(K_2(K)/p)\) be the filtration on \(K_2(K)/p\), induced from the filtration \(U^iK_2(K)\). We put \(\text{gr}^i(K_2(K)/p) = U^i(K_2(K)/p)/U^{i+1}(K_2(K)/p)\). Bloch and Kato [2] also determined the structure of \(\text{gr}^i(K_2(K)/p)\) for general complete discrete valuation field \(K\). In our case, (2) and (3) induce isomorphisms

(iii) \(\Omega^1_{E} \xrightarrow{\sim} \text{gr}^i(K_2(K)/p)\) for \(i = 1, 2, \ldots, p - 1, \text{and } p + 1\), and

(iv) \(F/F^p \xrightarrow{\sim} \text{gr}^p(K_2(K)/p)\) (\(x \mapsto \{1 + \pi^p\tilde{x}, \pi\}\)). Here, we have \(U^p(K_2(K)/p) = U^{p+1}K_2(K)\).

These results will be used in the subsequent sections.

**Corollary 1.3.** \(K\) does not have a cyclic extension which is totally ramified and which is of degree \(p^3\).

Proof. Let \(M/K\) be a totally ramified, cyclic extension of degree \(p^n\). In order to show \(n \leq 2\), since \(M/K\) is wildly ramified, it suffices to show that \(p^2(U^1K_2(K)/U^1K_2(K) \cap N_{M/K}K_2(M)) = 0\) where \(N_{M/K}\) is the norm map. In fact, if \(K\) is a 2-dimensional local field in the sense of Kato [8] and Parshin [18], this is clear from the isomorphism theorem of local class field theory

\[K_2(K)/N_{M/K}K_2(M) \simeq \text{Gal}(M/K).\]

In general case, \(U^1K_2(K)/U^1K_2(K) \cap N_{M/K}K_2(M)\) contains an element of order \(p^n\) by Lemma (3.3.4) in [12]. So it suffices to show

\[p^2(U^1K_2(K)/U^1K_2(K) \cap N_{M/K}K_2(M)) = 0.\]

We will first prove that \(U^{p+2}K_2(K) \subset N_{M/K}K_2(M)\). If \(j\) is sufficiently large, \(U^j_K = 1 + m^j_K\) is in \((K^\times)^{p^n}\), so \(U^jK_2(K)\) is in \(p^nK_2(K)\), hence in \(N_{M/K}K_2(M)\). So by Theorem 1.1, in order to prove \(U^{p+2}K_2(K) \subset N_{M/K}K_2(M)\), it suffices to show \(\{U^{2p}_K, \pi\}\) is in \(N_{M/K}K_2(M)\). Since \(M/K\) is totally ramified, there is a prime element \(\pi'\) of \(O_K\) such that \(\pi' \in N_{M/K}(M^\times)\). Hence, the subgroup \(\{U^{2p}_K, \pi'\}\) is contained in \(N_{M/K}K_2(M)\).
We note that \( \{ U^i_K, \pi \} \) is generated by \( \{ U^i_K, \pi' \} \) and \( \mathcal{U}^i K_2(K) \) for all \( i > 0 \). Hence, Theorem 1.1 also tells us that \( \{ U^{2p}_K, \pi \} \) is generated by \( \{ U^{2p}_K, \pi' \} \) and \( \mathcal{U}^j K_2(K) \) for sufficiently large \( j \). This shows that \( \{ U^{2p}_K, \pi \} \) is in \( N_{M/K} K_2(M) \), and \( \mathcal{U}^{p+2} K_2(K) \subset N_{M/K} K_2(M) \).

Since \( (U^1_K)^{p+2} \subset U^{p+2} K_2(K) \), we get \( p^2 U^1 K_2(K) \subset U^{p+2} K_2(K) \), and \( p^2 (U^1 K_2(K)/U^1 K_2(K) \cap N_{M/K} K_2(M)) = 0 \). This completes the proof of Corollary 1.3.

In order to describe the structure of \( K_2(K) \), we need the following exponential homomorphism introduced in [12] Lemma 2.4 (see also Lemma 2.2 in §2). We define \( K_2(K) \) (resp. \( \Omega^1_{O_K} \)) to be the \( p \)-adic completion of \( K_2(K) \) (resp. \( \Omega^1_{O_K} \)). Then, there is a homomorphism

\[
\exp_{p^2} : \Omega^1_{O_K} \longrightarrow K_2(K)^\wedge
\]

such that \( a \cdot db \mapsto \{ \exp(p^2 ab), b \} \) for \( a \in O_K \) and \( b \in O_K \setminus \{ 0 \} \). Here \( \exp(x) = \Sigma_{n \geq 0} x^n/n! \). Concerning \( K_2(K)^\wedge \), we have

**Corollary 1.4.** Let \( K \) be as in Theorem 1.1. Then, the image of

\[
\exp_{p^2} : \Omega^1_{O_K} \longrightarrow K_2(K)^\wedge
\]

is \( \mathcal{U}^{2p} K_2(K)^\wedge \) and the kernel is the \( \mathbb{Z}_p \)-module generated by \( da \) with \( a \in O_K \) and \( b(pd\pi/\pi - dT/T) \) with \( b \in O_K \).

We will prove this corollary in the end of §3.

2. \( p \)-torsions of \( K_2(K) \)

Let \( \zeta \) be a primitive \( p \)-th root of unity. We define \( L_0 = K_0(\zeta) \) and \( L = K(\zeta) = L_0(\pi) \) where \( \pi^n = pT \) as in Theorem 1.1.

Let \( \{ U^i K_2(L) \} \) be the filtration on \( K_2(L) \) defined similarly \( U^i K_2(L) \) is a subgroup generated by \( \{ 1 + m_L^i L^x \} \) where \( m_L \) is the maximal ideal of \( O_L \). Since \( L/K \) is a totally ramified extension of degree \( p - 1 \), we have natural maps \( U^i K_2(K) \longrightarrow U^{(p-1)i} K_2(L) \).

We also use the filtration \( U^i(K_2(L)/p) \) on \( K_2(L)/p \), induced from the filtration \( U^i K_2(L) \). If \( \eta \) is in \( U^i(K_2(L)/p) \setminus U^{i+1}(K_2(L)/p) \), we write \( \text{fil}_L(\eta) = i \). We also note that since \( L/K \) is of degree \( p - 1 \), \( U^i(K_2(K)/p) \longrightarrow U^{(p-1)i}(K_2(L)/p) \) is injective.

Our aim in this section is to prove the following Lemma 2.1.

**Lemma 2.1.** Suppose \( a \in U_{K_0} = O_{K_0}^\times \).

1. We have \( \{ \zeta, 1 + (\pi^i/(\zeta - 1))a \} \equiv \{ 1 - \pi^i a, T \} \pmod{U^{(p-1)i+1} K_2(L)} \) for \( i > 1 \).
(2) We regard \(\{\zeta, 1 + (\pi^i/(\zeta - 1))a\}\) as an element of \(K_2(L)/p\). For \(i = 2, \ldots, p - 1\) and \(p + 1\), we have
\[
\operatorname{fil}_L(\{\zeta, 1 + (\pi^i/(\zeta - 1))a\} \mod p) = (p - 1)i.
\]
If \(i = p\), then \(\operatorname{fil}_L(\{\zeta, 1 + (\pi^p/(\zeta - 1))a\} \mod p) > (p - 1)p\).

(3) For \(i = p + 2\),
\[
\{\zeta, 1 + (\pi^{p+2}/(\zeta - 1))a\} = \{\exp(\pi^{p+2}a), p\}
\]
in \(K_2(L)^\wedge\) where \(K_2(L)^\wedge\) is the \(p\)-adic completion of \(K_2(L)\) and \(\exp(x) = \sum_{n \geq 0} x^n/n!\).

(4) For \(i > p + 2\), \(\{\zeta, 1 + (\pi^i/(\zeta - 1))a\} = 0\) in \(K_2(L)^\wedge\).

We introduced the map \(\exp_{p^2}\) in Corollary 1.4, but more generally, we can define \(\exp_p\) as in the following lemma, whose proof will be done in Appendix Corollary A2.10 (see also Remark A2.11). The existence of \(\exp_{p^2}\) follows at once from the existence of \(\exp_p\). For more general exponential homomorphism (\(\exp_c\) with smaller \(v_K(c)\)), see [15].

**Lemma 2.2.** Let \(K\) be a complete discrete valuation field of mixed characteristics \((0, p)\). As in \(\S 1\), we denote by \(K_2(K)^\wedge\) (resp. \(\Omega^1_{O_K}\)) the \(p\)-adic completion of \(K_2(K)\) (resp. \(\Omega^1_{O_K}\)). Then there exists a homomorphism
\[
\exp_p : \Omega^1_{O_K} \rightarrow K_2(K)^\wedge
\]
such that \(a \cdot db \mapsto \{\exp(pab), b\}\) for \(a \in O_K\) and \(b \in O_K \setminus \{0\}\).

We use the following consequence of Lemma 2.2.

**Corollary 2.3.** In the notation of Lemma 2.2, we have
\[
\{1 + p^2c, p\} = 0 \quad \text{in} \quad K_2(K)^\wedge
\]
for any \(c \in O_K\).

**Proof.** In fact, \(\{1 + p^2c, p\} = \exp_p(p^{-2} \log(1 + p^2c) \cdot dp)\). Hence, by Lemma 2.2 and \(dp = 0\), we get the conclusion.

We also use the following lemma in Kato [7].

**Lemma 2.4.** (Lemma 6 in [7]) If \(x \neq 0, 1\), and \(y \neq 1, x^{-1}\),
\[
\{1 - x, 1 - y\} = \{1 - xy, -x\} + \{1 - xy, 1 - y\} - \{1 - xy, 1 - x\}
\]

**Proof of Lemma 2.4.**
\[
\{1 - x, 1 - y\} = \{1 - x, x(1 - y)\} = \{1 - x, -(1 - x) - (1 - xy)\}
\]
\[
= \{1 - x, 1 - \frac{x - xy}{1 - x}\} = \{1 - xy, 1 - \frac{1 - xy}{1 - x}\}
\]
\[
= \{1 - xy, -(1 - y)(1 - x)^{-1}\}.
\]
Using this lemma, we have
\[
\{\zeta, 1 + (\pi^i/ (\zeta - 1))a\} = \\
\{1 - \pi^i a, \zeta - 1\} + \{1 - \pi^i a, 1 + (\pi^i/ (\zeta - 1))a\} + \{\zeta, 1 - \pi^i a\}  \tag{4}
\]

Put \(\pi_L = (\zeta - 1)/\pi\), and \(u = p/(\zeta - 1)^{p-1}\). Then \(\pi_L\) is a prime element of \(O_L\), and \(u\) is a unit of \(\mathbb{Z}_p[\zeta]\). Since \(\pi^p = pT\), we have
\[
\zeta - 1 = u\pi^p T.  \tag{5}
\]

Since \(u = v^p(1 + w(\zeta - 1))\) for some \(v, w\) in \(\mathbb{Z}_p[\zeta]\), by (4) and (5) we get
\[
\{\zeta, 1 + (\pi^i/ (\zeta - 1))a\} \equiv \{1 - \pi^i a, T\} \pmod{U^{(p-1)i+1}K_2(L)}.  \tag{6}
\]

Thus, we obtain Lemma 2.1 (1).

Put \(x = a \pmod{p} \in F\). Lemma 2.1 (2) follows from Lemma 2.1 (1). In fact, if \(1 < i < p\) or \(i = p+1, \{1 - \pi^i a, T\} \pmod{p}\) is not in \(U^{i+1}(K_2(K)/p)\) by Remark 1.2 (iii) (note that \(x \neq 0\) and \(x \cdot dt/t \neq 0\)). Hence, it is not in \(U^{(p-1)i+1}(K_2(L)/p)\). So, \(\text{fil}_L(\{1 - \pi^i a, T\} \pmod{p}) = (p-1)i\). For \(i = p, \{1 - \pi^p a, T\} \pmod{p}\) is in \(U^{p+1}(K_2(K)/p)\). In fact, we may suppose \(a = \Sigma b_i T^i\) for some \(b_i \in O_K\), then \(\{1 - \pi^p a, T\} \equiv \Sigma_{i>1} (1 - b_i T^i, T) = -\Sigma_{i>1} \{1 - b_i T^i, b_i T\} \equiv 0 \pmod{U^{p+1}(K_2(K)/p)}\) (cf. Remark 1.2 (iv)). Hence, \(\text{fil}_L(\{1 - \pi^p a, T\} \pmod{p}) > (p-1)p\).

If \(p > 3\) or \(i > p + 3\), Lemma 2.1 (4) is easy because \(1 + (\pi^i/ (\zeta - 1))a\) is in \(U^{p+1}_L \subset (L^\times)^p\) (Note that \(e_Lp/(p-1) = p^2\)). We deal with the case \(p = 3\) and \(i = p + 3\) in the end of this section.

We proceed to the proof of Lemma 2.1 (3). Since \((1 + (\pi^{p+2}/ (\zeta - 1))a)/(1 + (\pi^{p+2}/ (\zeta - 1))a\zeta) \in U^{p+2}_L \subset (L^\times)^p\),
\[
\{\zeta, 1 + (\pi^{p+2}/ (\zeta - 1))a\} = \{\zeta, 1 + (\pi^{p+2}/ (\zeta - 1))a\zeta\}.  \tag{7}
\]

By Lemma 2.2, we have
\[
\{\zeta, 1 + (\pi^{p+2}/ (\zeta - 1))a\zeta\} = \{\zeta, \exp(\pi^{p+2}a\zeta/(\zeta - 1))\}
= -\exp_p((\pi^2Ta/ (\zeta - 1))d\zeta)
= -\exp_p((\pi^2Ta/ (\zeta - 1))d(\zeta - 1))
= -\{\exp(\pi^p a), \zeta - 1\}.  \tag{8}
\]

Hence by (5) (6) and (7), we obtain
\[
\{\zeta, 1 + (\pi^{p+2}/ (\zeta - 1))a\} = -\{\exp(\pi^p a), u\}
- p\{\exp(\pi^p a), \pi_L\}
- \{\exp(\pi^p a), T\}.  \tag{8}
\]

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First of all, \( \{ \exp(\pi^{p+2}a), u \} = 0 \) in \( K_2(L)^\wedge \). In fact, if we write \( du = w \cdot d\zeta \) for some \( w \in \mathbb{Z}_p[\zeta] \),
\[
\{ \exp(\pi^{p+2}a), u \} = \exp_p(\pi^2Ta \cdot du/u) \\
= \exp_p(\pi^2Ta u^{-1}w \cdot d\zeta) \\
= \{ \exp(\pi^{p+2}aw\zeta u^{-1}), \zeta \}.
\]

Since \( \exp(\pi^{p+2}aw\zeta u^{-1}) \) is in \( U_L^{p^2+1} \subset (L^\times)^p \), \( \{ \exp(\pi^{p+2}a), u \} = 0 \).

By the same method, \( p\{ \exp(\pi^{p+2}a), \zeta - 1 \} = 0 \), hence the second term of the right hand side of (8) is equal to \( p\{ \exp(\pi^{p+2}a), \pi \} \) (from \( \pi_L = (\zeta - 1)/\pi \)). Hence by (8) we have
\[
\{ \zeta, 1 + (\pi^{p+2}/(\zeta - 1))a \} = \{ \exp(\pi^{p+2}a), \pi^p/T \} = \{ \exp(\pi^{p+2}a), p \}
\]
(recall that \( \pi^p = pT \)). Thus, we have got Lemma 2.1 (3).

We go back to Lemma 2.1 (4). For \( p = 3 \) and \( i = p + 3 \), by the same method, we obtain
\[
\{ \zeta, 1 + (\pi^{p+3}/(\zeta - 1))a \} = \{ \exp(\pi^{p+3}a), p \}.
\]
But the right hand side is zero by Corollary 2.3.

### 3. Proof of the theorem

**3.1.** First of all, we prove Theorem 1.1 (1). Let \( i \) be an integer such that \( p + 1 < i \). Then by Lemma 2.1 (1), we have
\[
\{ \zeta, 1 + (\pi^{i-p}/(\zeta - 1))aT \} \equiv \{ 1 - \pi^{i-p}aT, T \} \pmod{U^{(p-1)(i-p)+1}K_2(L)}
\]
for \( a \in O_{K_0} \). Hence, taking the multiplication by \( p \), we get
\[
0 \equiv \{ 1 - p\pi^{i-p}aT, T \} = \{ 1 - \pi^i a, T \} \pmod{U^{(p-1)i+1}K_2(L)}.
\]
This implies \( \{ 1 - \pi^i a, T \} \equiv 0 \pmod{U^{i+1}K_2(K)} \). Since \( U^iK_2(K) = U^iK_2(K) \) for all \( i \) with \( (i, p) = 1 \) and the surjectivity of (2) implies that \( U^iK_2(K)/U^{i+1}K_2(K) \) is generated by the image of \( \{ U^iK, T \} \), it follows from \( \{ 1 - \pi^i a, T \} \in U^{i+1}K_2(K) \) that \( U^iK_2(K) = U^{i+1}K_2(K) \) for all \( i \) with \( (i, p) = 1 \).

We remark that by [12] Theorem 2.2, if \( i > 2p \) and \( i \) is prime to \( p \), we already knew \( gr^iK_2(K) = 0 \) ([\( \hat{\Omega}_{O_K} \)] tors is generated by \( \pi^{p-1}d\pi - dT \), and isomorphic to \( O_K/(p) \)). So the problem was only to show \( gr^iK_2(K) = 0 \) for \( i \) such that \( p + 1 < i < 2p \).

**3.2.** Next we proceed to \( i = 2p \). By \( \pi^p = pT \), we have \( p \cdot dT = p\pi^p \cdot d\pi/\pi \).

Hence, \( \exp_p(p \cdot dT) = \exp_p(p\pi^p \cdot d\pi/\pi) \), namely
\[
\{ \exp(p^2aT), T \} = \{ \exp(p^2\pi^p a), \pi \} \ \text{in} \ \ K_2(K)^\wedge
\]
for all \( a \in O_K \). Hence, \( U^{2p}K_2(K) \subset U^{2p+1}K_2(K) \) and
\[
\text{gr}^{2p}K_2(K) = U^{2p}K_2(K)/U^{2p+1}K_2(K)
\]
(this also follows from [12] Theorem 2.2).

For \( a \in U_{K_0} \), by an elementary calculation
\[
\{1 - p\pi^pa^p, \pi\} \equiv p\{1 - \pi^pa^p, \pi\} \pmod{U^{2p+1}K_2(K)}
\]
\[= \{1 - \pi^pa^p, \pi\} = \{1 - p\pi^pa^p, 1/a^p\} \]
\[\equiv -\{1 - p\pi^pa^p, a\}, \]
we know that \( F^p \) is contained in the kernel of the map \( x \mapsto \{1 + p\pi^p\tilde{x}, \pi\} \)
in (3) from \( F \) to \( \text{gr}^{2p}K_2(K) \) because of \( U^{2p}K_2(K) = U^{2p+1}K_2(K) \).

Next we assume that \( a \in U_{K_0} \) and \( x = a \mod p \) is not in \( F^p \). We will prove \( \{1 + p\pi^pa, \pi\} \notin U^{2p+1}K_2(K) \). Let \( L = K(\zeta), U^i(K_2(L)/p), \text{fil}_L(\eta) \) be as in §2. Since \( x \notin F^p \), by Remark 1.2 (iv) we have \( \text{fil}_K(\{1 + p\pi^pa, \pi\} \mod p) = p \) and
\[
\text{fil}_L(\{1 + p\pi^pa, \pi\} \mod p) = (p - 1)p. \quad (9)
\]

Let \( \Delta = \text{Gal}(L/K) \) be the Galois group of \( L/K \). Consider the following commutative diagram of exact sequences
\[
(L^\times/(L^\times)^p(1))^\Delta \xrightarrow{\rho_1} K_2(L)/p \xrightarrow{\rho_2} K_2(L)/p^2
\]
\[
H^1(K, \mathbb{Z}/p(2)) \longrightarrow H^2(K, \mathbb{Z}/p(2)) \longrightarrow H^2(K, \mathbb{Z}/p^2(2))
\]
where \( \rho_1 \) is the restriction to the \( \Delta \)-invariant part \( (L^\times/(L^\times)^p(1))^\Delta \) of the map \( L^\times/(L^\times)^p(1) \longrightarrow K_2(L)/p; x \mapsto \{\zeta, x\} \) (we used \( (K_2(L)/p)^\Delta \cong K_2(L)/p \)), and \( \rho_2 \) is the map induced from the multiplication by \( p \) (\( \alpha \mod p \mapsto p\alpha \mod p^2 \)). The left vertical arrow is bijective, and the central and the right vertical arrows are also bijective by Mercurjev and Suslin.

This diagram says that the kernel of \( \rho_2 \) is equal to the image of \( \{\zeta, L^\times\}^\Delta \) in \( K_2(L)/p \). The filtration \( U^i_L = 1 + m^i_L \) on \( L^\times \) induces a filtration on \( (L^\times/(L^\times)^p(1))^\Delta \), and its graded quotients are calculated as \( (U^i_L/U^{i+1}_L)^\Delta = U^i_L/U^{i+1}_L \) if \( i \equiv -1 \mod p - 1 \), and \( = 0 \) otherwise (\( (L^\times/U^i_L \otimes \mathbb{Z}/p(1))^\Delta \) also vanishes). Since the image of \( 1 + \{\pi^i(\zeta - 1)\}U_{K_0} \) generates \( U^{(p-1)i-p}/U^{(p-1)i-p+1}_L \), if \( \eta \) is in Image \( \rho_1 \subset (K_2(L)/p)^\Delta \), then \( \eta \) can be written as \( \eta \equiv \{\zeta, 1 + \{\pi^i(\zeta - 1)\}a_i\} \mod U^{(p-1)i+1}_LK_2(L) \) for some \( i > 0 \) with \( a_i \in U_{K_0} \). Hence, by Lemma 2.1 (2), we have \( \text{fil}_L(\eta) \neq (p - 1)p \).

Therefore by (9), \( \{1 + p\pi^pa, \pi\} \) does not belong to \( \{\zeta, L^\times\}^\Delta \) in \( (K_2(L)/p)^\Delta = K_2(L)/p \). So by the above exact sequence,
\[
\{1 + p\pi^pa, \pi\} \neq 0 \quad \text{in} \quad K_2(K)/p^2.
\]
Since \( U^{2p+1}K_2(K) = U^{3p}K_2(K) \subset p^2K_2(K) \), this implies that \( \{1 + p\pi^pa, \pi\} \neq 0 \) in \( \text{gr}^{2p}K_2(K) \). Hence, the kernel of the map \( x \mapsto \{1 + p\pi^p\tilde{x}, \pi\} \) from
3.3. We next prove (3) of Theorem 1.1. Let \( n \geq 3 \). By the same method as in 3.2, we have \( \mathcal{U}^{np}K_2(K) = U^{np+1}K_2(K) \) (this also follows from [12] Theorem 2.2), in particular, the map

\[
\mathcal{F} \rightarrow \text{gr}\, K_2^n(K) \quad (x \mapsto \{1 + p^n\bar{x}, \pi\})
\]

(10)
is surjective.

Suppose that \( a \in O_{K_0} \). By Corollary 2.3, we have \( \{\exp(p^{n-1}a), p\} = 0 \) in \( K_2^n(K)^{\wedge} \), hence we get

\[
\{\exp(p^n a), \pi\} = \{\exp(p^{n-1}a), \pi^p\} = \{\exp(p^{n-1}a), pT\} = \{\exp(p^{n-1}a), T\}.
\]

(11)

Since \( n \geq 3 \), the above formula implies

\[
\{1 + p^n a, \pi\} \equiv \{\exp(p^n a), \pi\} \quad (\text{mod } U^{(n+1)p}K_2(K))
\]

\[
= \{\exp(p^{n-1}a), T\}
\]

\[
\equiv \{1 + p^{n-1}a, T\} \quad (\text{mod } U^{(n+1)p}K_2(K)).
\]

(12)

Recall that we fixed a \( p \)-base \( t \) of \( F \) such that \( T \mod p = t \). We define subgroups \( \mathcal{B}_n \) of \( F \) by \( \mathcal{B}_n dt/t = \mathcal{B}_n \Omega^1_F \) for \( n > 0 \). Suppose that \( x \) is in \( \mathcal{B}_{n-2} \). Let \( a = \bar{x} \) be a lifting of \( x \) to \( O_{K_0} \). Then by [14] Proposition 2.3, we get

\[
\{1 + p^{n-1}a, T\} \in U^n K_2(K_0).
\]

(13)

Let \( i_{K/K_0} : K_2(K_0) \rightarrow K_2(K) \) be the natural map. Then, we have \( i_{K/K_0}(U^n K_2(K_0)) \subset U^{np}K_2(K) \), but by the formula (11), \( i_{K/K_0}(U^{n-1} K_2(K_0)) \subset U^{np} K_2(K) \) also holds. Hence by (12), (13), and \( i_{K/K_0}(U^n K_2(K_0)) \subset U^{(n+1)p} K_2(K) \), we know that \( \{1 + p^n a, \pi\} \) is in \( U^{(n+1)p} K_2(K) \). Namely, \( \mathcal{B}_{n-2} \) is in the kernel of the map (10).

Since \( B_{n-2} \Omega^1_F \) is generated by the elements of the form \( x^{p^{n-2}} ti \cdot dt/t \) such that \( x \in \mathcal{F} \) and \( 1 \leq i \leq p^{n-2} - 1 \), \( F/\mathcal{B}_{n-2} \) is isomorphic to \( F^{p^{n-2}} \), and we obtain a surjective homomorphism

\[
F^{p^{n-2}} \rightarrow \text{gr}\, K_2^n(K); \quad x \mapsto \{1 + p^n\bar{x}, \pi\}.
\]

(14)

We proceed to the proof of the injectivity of (14). We assume that \( \{1 + p^n a, \pi\} \) is in \( U^{np+1} K_2(K) \) for \( a \in O_{K_0} \). Since \( U^{np+1} K_2(K) = U^{(n+1)p} K_2(K) \subset p^n K_2(K) \), \( \{1 + p^n a, \pi\} = 0 \) in \( K_2(K)/p^n \). Hence \( \{1 + p^n a, \pi\} \) is in the kernel of \( K_2(K)/p^{n-1} \rightarrow K_2(K)/p^n \) (\( \alpha \mod p^{n-1} \mapsto \ldots \)}
As in 3.2, we consider a commutative diagram of exact sequences with vertical bijective arrows

\[
\begin{array}{ccc}
(L^\times/(L^\times)^p(1))^\Delta & \xrightarrow{\rho_1} & K_2(K)/p^{n-1} \\
\downarrow & & \downarrow \\
H^1(K, \mathbb{Z}/p(2)) & \rightarrow & H^2(K, \mathbb{Z}/p^{n-1}(2)) \rightarrow H^2(K, \mathbb{Z}/p^n(2))
\end{array}
\]

where \(\rho_1\) is the restriction to \((L^\times/(L^\times)^p(1))^\Delta\) of the map \(L^\times/(L^\times)^p(1) \rightarrow K_2(L)/p^{n-1}\); \(x \mapsto \{\zeta, x\}\) (we also used \((K_2(L)/p^{n-1})^\Delta \simeq K_2(K)/p^n\)). From this diagram, we know that \(\{1 + p^{n-1}a, \pi\}\) is in the image of \(\rho_1\). We write \(\{1 + p^{n-1}a, \pi\} = \{\zeta, c\}\) for some \(c \in (L^\times/(L^\times)^p(1))^\Delta\). So by the argument in 3.2, \(c\) is in \(U^{(p-1)i-p}_L\) for some \(i > 1\). If \(c\) was in \(U^{(p-1)i-p}_L \setminus U^{(p-1)(i+1)-p}_L\) for some \(i\) with \(1 < i < p\), we would have by Lemma 2.1 (2) \(\text{fil}_L(\{\zeta, c\} \mod p) = (p-1)i\). But \(\{1 + p^{n-1}a, \pi\}\) is zero in \(K_2(L)/p\) (because \(1 + p^{n-1}a \in (L^\times)^p\)), so \(c\) must be in \(U^{(p-1)p-p(1)}_L\). We write \(c = c_1c_2\) with \(c_1 \in U^{p-2}_L(1)\Delta\) and \(c_2 \in U^{(p-1)(p+1)-p(1)}_L\). Again by the same argument using Lemma 2.1 (2), \(c_2\) must be in \(U^{(p-1)(p+2)-p(1)}_L\). By Lemma 2.1 (3) and (4), we can write

\[
\{1 + p^{n-1}a, \pi\} = \{\zeta, c_1\} + \{\exp(\pi^{p+2}c_3), p\}
\]

for some \(c_3 \in O_{K_0}\) in \(K_2(L)/p^{n-1}\). Let \(N_{L/L_0} : K_2(L) \rightarrow K_2(L_0)\) be the norm homomorphism. Taking the norm \(N_{L/L_0}\) of the both sides of the equation (15), we get

\[
\{1 + p^{n-1}a, pT\} = \{\zeta, c_1^p\} + \{\exp(\text{Tr}_{L/L_0}(\pi^{p+2}c_3)), p\} = 0
\]

where \(\text{Tr}_{L/L_0}\) is the trace, and we used \(\text{Tr}_{L/L_0}(\pi^{p+2}c_3) = pTc_3 \text{Tr}_{L/L_0}(\pi^2) = 0\). On the other hand, the left hand side of (16) is equal to \(\{1 + p^{n-1}a, T\}\) by Corollary 2.3. Hence, the equation (16) implies that \(\{1 + p^{n-1}a, T\} = 0\) in \(K_2(L_0)/p^{n-1}\), hence in \(K_2(K_0)/p^{n-1}\).

In the proof of [14] Corollary 2.5, we showed that \(\exp_{p^2}\) induces

\[
\exp_{p^2} : (\Omega_{O_{K_0}}^1/dO_{K_0}) \otimes \mathbb{Z}/p^{n-2} \rightarrow K_2(K_0)/p^{n-1}
\]

which is injective. In \(K_2(K_0)/p^{n-1}\), we have \(\{\exp(p^{n-1}a), T\} = \{1 + p^{n-1}a, T\} = 0\), hence by the injectivity of the above map, we know that \(p^{n-3}adT/T \mod p^{n-2}\) is in \(d(O_{K_0}/p^{n-2})\). This implies that \(x \cdot dt/t\) is in \(B_{n-2}\mathcal{O}_F\), where \(x = a \mod p \in F\) ([6] Corollaire 2.3.14 in Chapter 0). Hence, \(x\) is in \(B_{n-2}\). Thus, the kernel of the map (10) coincides with \(B_{n-2}\). Namely, the map (14) is bijective. This completes the proof of Theorem 1.1.
3.4. Finally we prove Corollary 1.4. Let $M$ be the $\mathbb{Z}_p$-submodule of $\hat{\Omega}^1_{O_K}$ generated by $da$ with $a \in O_K$ and $b(pd\pi/\pi - dt/T)$ with $b \in O_K$. It follows from $\pi^p = pT$ that $p^{n-1}a\pi^p/\pi = p^2Td\pi/\pi = pdT$ in $\hat{\Omega}^1_{O_K}$. Hence, the existence of $\exp_p$ implies that $b(pd\pi/\pi - dT/T)$ is in the kernel of $\exp_p$. Further, $da$ is also in the kernel of $\exp_p$ by Lemma A2.3 in Appendix. So $\exp_p$ factors through $\hat{\Omega}^1_{O_K}/M$. Since $b(pd\pi/\pi - dT/T) \in M$, $\hat{\Omega}^1_{O_K}/M$ is generated by the classes of $cd\pi/\pi$ with $v_K(c) \geq i - 2p$, and consider $gr^i = \text{Fil}^i/\text{Fil}^{i+1}$.

We can easily see that $gr^i = 0$ for $i$ which is prime to $p$. In fact, if $i$ is prime to $p$, for $a \in U_K$, $a\pi^i d\pi/\pi = a\pi^{i-1}d\pi^i \equiv -\pi^i da \pmod{M}$. We can write $da = a_1dT + a_2d\pi \equiv a_1Td\pi/\pi + a_2\pi d\pi/\pi \pmod{M}$ for some $a_1$, $a_2 \in O_K$, hence $a\pi^i d\pi/\pi$ is in $\text{Fil}^{i+1}$. For $i \leq 2p$, we also have $gr^i = 0$.

Suppose that $n \geq 3$ and consider a homomorphism

$$F \longrightarrow gr^{np}; \quad x \mapsto p^{n-2}x d\pi/\pi. \quad (17)$$

This does not depend on the choice of $\bar{x}$. Suppose that $x$ is in $B_{n-2}$ (for $B_{n-2}$, see the previous subsection). We write $x = \Sigma_{i=1}^{p^{n-2}-1} x_i^{p^{n-2}} T_i \cdot dt/T$ as in 3.3, and take a lifting $a = \Sigma_{i=1}^{p^{n-2}-1} \bar{x} x_i^{p^{n-2}} T_i \cdot dt/T$ where $\bar{x}_i$ is a lifting of $x_i$ to $O_{K_0}$. We have $p^{n-2} ad\pi/\pi \equiv p^{n-2} b dT/T \pmod{M} \equiv db \pmod{\text{Fil}^{np}}$ for some $b \in O_{K_0}$. Hence, $p^{n-2} ad\pi/\pi \in M$, and $B_{n-2}$ is in the kernel of $(17)$. So the restriction of $(17)$ to $F^{p^{n-2}}$ gives a surjective homomorphism $F^{p^{n-2}} \longrightarrow gr^{np}$ as in 3.3. This is also injective because the composite $F^{p^{n-2}} \longrightarrow gr^{np} \longrightarrow gr^{np} K_2(K)$ with the induced map by $\exp_p$ is bijective by Theorem 1.1 (3). Therefore, comparing $gr^i$ with $gr^i K_2(K)$, we know that $\exp_p : \hat{\Omega}^1_{O_K}/M \longrightarrow \mathcal{U}^{np} K_2(K)$ is bijective.

### Appendix A. Milnor $K$-groups of a local ring over a ring of $p$-adic integers

In this appendix, we show the existence of $\exp_p$ (Corollary A2.10). To do so, we describe the Milnor $K$-groups of a local ring over a complete discrete valuation ring of mixed characteristics, by using the modules of differentials with certain divided power envelopes. (For the precise statement, see Proposition A1.3 and Theorem A2.2.) This description is related to the theory of syntomic cohomology developed by Fontaine and Messing.

On a variety over a complete discrete valuation ring of mixed characteristics, Fontaine and Messing [4] developed the theory of syntomic cohomology which relates the etale cohomology of the generic fiber with the crystalline cohomology of the special fiber. In [9] Kato studied the image of the syntomic cohomology in the derived category of the etale sites, and considered the syntomic complex on the etale site. He also used the Milnor $K$-groups
in order to relate the syntomic complex with the $p$-adic étale vanishing cycles, and obtain an isomorphism between the sheaf of the Milnor $K$-groups and the cohomology of the syntomic complex after tensoring with an algebraically closed field ([9] Chap.I 4.3, 4.11, 4.12). Our description of the Milnor $K$-groups says that this isomorphism exists without tensoring with an algebraically closed field (for the precise statement cf. Remark A2.12 (28)). This appendix is a part of the author’s master’s thesis in 1986.

A.1. Smooth case.

A.1.1. Let $\Lambda$ be a complete discrete valuation ring of mixed characteristics $(0, p)$. We further assume that $p$ is an odd prime number, and that $\Lambda$ is absolutely unramified, namely $p\Lambda$ is the maximal ideal of $\Lambda$. We denote by $F = \Lambda/p\Lambda$ the residue field of $\Lambda$.

Let $(R, m_R)$ be a local ring over $\Lambda$ such that $R/pR$ is essentially smooth over $F$, and $R$ is flat over $\Lambda$. Further, we assume that $R$ is $p$-adically complete, i.e. $R \cong \lim \leftarrow R/p^n R$, and define $B = R[[X]]$. In this section, we study the Milnor $K$-group of $B$. (One can deal with more general rings by the method in this section, but for simplicity we restrict ourselves to the above ring.)

Since $R/pR$ is essentially smooth over $F$, $R/pR$ has a $p$-base. Namely, there exists a family $(e_\lambda)_{\lambda \in L}$ of elements of $R/pR$ such that any $a \in R/pR$ can be written uniquely as

$$a = \sum_s a_s \prod_{\lambda \in L} e_\lambda^{s(\lambda)}$$

where $a_s \in R/pR$, and $s$ ranges over all functions $L \rightarrow \{0, 1, \ldots, p - 1\}$ with finite supports.

For a ring $A$, $\Omega^1_A$ denotes the module of Kähler differentials. Let $e_\lambda$ be as above, then $\{de_\lambda\}$ is a basis of the free module $\Omega^1_{R/pR}$. We consider a lifting $I \subset R$ of a $p$-base $\{e_\lambda\}$. Then $\{dT; T \in I\}$ gives a basis of the free $R$-module $\check{\Omega}^1_R$, where $\check{\Omega}^1_R$ is the $p$-adic completion of $\Omega^1_R$. Since $R$ is local, we can take $I$ from $R^\times$. In the following, we fix $I$ such that $I \subset R^\times$.

For the lifting $I$ of a $p$-base, we can take an endomorphism $f$ of $R$ such that $f(T) = T^p$ for any $T \in I$, and that $f(x) \equiv x^p \pmod{p}$ for any $x \in R$. We fix this endomorphism $f$, and call it the Frobenius endomorphism relative to $I$.

We put $B = R[[X]]$. We extend $f$ to an endomorphism of $B$ by $f(X) = X^p$. So $f$ satisfies $f(x) \equiv x^p \pmod{p}$ for any $x \in B$. Let $XB$ be the ideal of $B$ generated by $X$.

Lemma A.1.1. Put $f_1 = \frac{1}{p} f : B[1/p] \rightarrow B[1/p]$, $f^n_1 = f_1 \circ \ldots \circ f_1$ ($n$ times), and $E_1 = \exp(\sum_{n=0}^{\infty} f^n_1)$. Then, for $a \in B$, $E_1(aX)$ is in $B^\times$, and
E₁ defines a homomorphism (Shafarevich function)
\[ E₁ : XB \to B^\times. \]

It suffices to show \( E₁(aX) \) is in \( B^\times \) for \( a \in B \). We define \( a_n \in B \) inductively by \( a_0 = a \) and
\[
f^n(a) = W_n(a_0, a_1, ..., a_n)
\]
where \( f^n = f \circ ... \circ f \) (n times), and \( W_n(T_0, ..., T_n) \) is the Witt polynomial ([19] Chap.II). (It is easily verified that \( f^n(a) - (ap^n + pa^{n-1} + ... + p^{n-1}a_{n-1}) \) is divisible by \( p^n \). Hence, \( a_n \) is well-defined.) By the formula of Artin-Hasse exponential \( \exp(\Sigma_{n=0}^{\infty} T^n/p^n) = \prod_{(p,m) = 1} (1 - T^m)^{-\mu(m)/m} \), we have
\[
E₁(aX) = \prod_{n=0}^{\infty} \prod_{(p,m) = 1} (1 - (a_nXp^n)^m)^{-\mu(m)/m}.
\]

Hence, \( E₁(aX) \in B^\times \).

**A.1.2.** Let \( \hat{\Omega}^1_B \) be the \((p, X)\)-adic completion of \( \Omega^1_B \). For an integer \( r \in \mathbb{Z} \), let \( \hat{\Omega}^r_B = \wedge^r \hat{\Omega}^1_B \) for \( r \geq 0 \), and \( \hat{\Omega}^r_B = 0 \) for \( r < 0 \). Let \( r \) be positive. Then \( f \) naturally acts on \( \hat{\Omega}^r_B \), and the image is contained in \( p^r \hat{\Omega}^r_B \). So we can define \( f_r = p^{-r}f \) on \( \hat{\Omega}^r_B \).

We define \( I_B = I \cup \{X\} \). Then \( \{dT_1 \wedge ... \wedge dT_r; T_i \in I_B \} \) is a base of \( \hat{\Omega}^r_B \). For \( i > 0 \) we define \( U^1 \hat{\Omega}^r_B \) to be the subgroup (topologically) generated by the elements of the form \( adT_1 \wedge ... \wedge dT_r \), and \( bdT_1 \wedge ... \wedge dT_{r-1} \wedge dX \) where \( a \in X^iB, b \in X^{i-1}B, \) and \( T_1, ..., T_r \in I \).

**A.1.3.** For a ring \( k \) and \( q \geq 0 \), the Milnor \( K \)-group \( K^M_q(k) \) is by definition
\[
K^M_q(k) := (k^x \otimes ... \otimes k^x)/J
\]
where \( J \) is the subgroup generated by the elements of the form \( a_1 \otimes ... \otimes a_q \) such that \( a_i + a_j = 0 \), or 1 for some \( i \neq j \). (The class of \( a_1 \otimes ... \otimes a_q \) is denoted by \( \{a_1, ..., a_q\} \).)

We will define a homomorphism \( E_q \) which is regarded as \( \exp(\Sigma_{n=0}^{\infty} f^n) \) from the module of the differential \((q - 1)\)-forms to the \( q \)-th Milnor \( K \)-group. First of all, we remark that in \( K^M_2(B) \), the symbol \( \{1 + Xa, X \} \) makes sense for \( a \in B \). Namely, for any \( x \) in the maximal ideal \( m_B \), we define \( (1 + xa, x) \) to be
\[
\{1 + xa, x\} = \begin{cases} 
\{-1 + xa, -a\} & \text{if } a \notin m_B \\
\{-(1 + a)/(1 - x), (1 + ax)/(1 - x)\} & \text{if } a \in m_B.
\end{cases}
\]

Then, usual relations like \( \{1 + xya, x\} + \{1 + xya, y\} = \{1 + xya, xy\} \), \( \{1 + xa, x\} + \{1 + xb, x\} = \{(1 + xa)(1 + xb), x\} \), \( \{1 - x, x\} = 0 \) hold, and the image of \( \{1 + xa, x\} \) in \( K^M_2(B[1/x]) \) is \( \{1 + xa, x\} \) ([22], [11]). Hence,
the notation \( \{1 + Xa, b_1, \ldots, b_{q-2}, X\} \) also makes sense in \( K_q^M(B) \) where \( b_i \in B^\times \).

We define \( K_q^M(B)^\wedge \) to be the \((p, X)\)-adic completion of \( K_q^M(B) \), namely the completion with respect to the filtration \( \{V_i\} \) where \( V_i \) is the subgroup generated by \( \{1 + (p, X)^i, B^\times, \ldots, B^\times\} \). Let \( U_i X K_q^M(B)^\wedge \) be the subgroup (topologically) generated by \( \{1 + X^i B, B^\times, \ldots, B^\times\} \) and \( \{1 + X^i B, B^\times, \ldots, B^\times, X\} \). We define

\[
E_q : U_X^1 \hat{\Omega}^{q-1}_B \longrightarrow K_q^M(B)^\wedge
\]

by

\[
aX \cdot \frac{dT_1}{T_1} \wedge \ldots \wedge \frac{dT_{q-1}}{T_{q-1}} \mapsto \{E_1(aX), T_1, \ldots, T_{q-1}\}
\]

where \( a \in B \) and \( T_i \in I_B \). Since \( f_q(aX \cdot (dT_1)/T_1 \wedge \ldots \wedge (dT_{q-1})/T_{q-1}) = f_1(aX) \cdot (dT_1)/T_1 \wedge \ldots \wedge (dT_{q-1})/T_{q-1} \), \( E_q \) can be regarded as \( \exp(\Sigma_{n=0}^\infty f_q^n) \).

Lemma A.1.2. \( E_q \) vanishes on \( U_X^1 \hat{\Omega}^{q-1}_B \cap d\hat{\Omega}^{q-2}_B = d(U_X^1 \hat{\Omega}^{q-2}_B) \).

We may assume \( q = 2 \). So we have to prove \( E_2(d(Xa)) = 0 \). By the additivity of the claim, we may assume that \( a \) is a product of elements of \( I_B \), namely \( a = \Pi T_i \) where \( T_i \in I_B \). In particular, \( f(a) = a^p \). Using \( Xa = \Pi T_i \), we have

\[
E_2(d(Xa)) = \sum \{E_1(Xa), XT_i\} = \{E_1(Xa), Xa\}
\]

\[
= \prod_{(p, m) = 1} (1 - (Xa)^m)^{-\mu(m)/m}, Xa
\]

\[
= \sum_{(p, m) = 1} -\mu(m)/m^2 \{1 - (Xa)^m, (Xa)^m\}
\]

\[
= 0.
\]

This completes the proof of Lemma 2.2.

A.1.4. For \( i > 0 \) we define \( U_X^i (\hat{\Omega}^{q-1}_B / d\hat{\Omega}^{q-2}_B) \) to be the image of \( U_X^i \hat{\Omega}^{q-1}_B \) in \( \hat{\Omega}^{q-1}_B / d\hat{\Omega}^{q-2}_B \).

Proposition A.1.3. \( E_q \) induces an isomorphism

\[
E_q : U_X^1 (\hat{\Omega}^{q-1}_B / d\hat{\Omega}^{q-2}_B) \xrightarrow{\sim} U_X^1 K_q^M(B)^\wedge
\]

which preserves the filtrations.

Proof. Using Vostokov’s pairing [23], Kato defined in [9] a symbol map

\[
h_q = (s_f, q, d \log) : K_q^M(B) \longrightarrow (\hat{\Omega}^{q-1}_B / d\hat{\Omega}^{q-2}_B) \oplus \hat{\Omega}^q_B
\]
such that

\[ s_{f,q}(\{a_1, \ldots, a_q\}) = \sum_{i=1}^{q} (-1)^{i-1} \frac{1}{p} \log \left( \frac{f(a_i)}{a_i^p} \right) a_1^{d_1} \wedge \ldots \wedge a_{i-1}^{d_{i-1}} \wedge \frac{f(a_{i+1})}{a_i^p} a_1^{d_1} \wedge \ldots \wedge \frac{f(a_q)}{a_q^p} a_1^{d_1} \]

and \( d \log \{a_1, \ldots, a_q\} = (da_1)/a_1 \wedge \ldots \wedge (da_q)/a_q \).

Concerning the map \( s_{f,q} \) we will give two remarks. If \( T_1, \ldots, T_{q-1} \) are in \( I_B \) (and \( \{a, T_1, \ldots, T_{q-1}\} \) is defined), then

\[ s_{f,q}(\{a, T_1, \ldots, T_{q-1}\}) = \frac{1}{p} \log \left( \frac{f(a)}{a^p} \right) \frac{dT_1}{T_1} \wedge \ldots \wedge \frac{dT_{q-1}}{T_{q-1}}. \]

Here, we are allowed to take \( T_1 = X \). To see this, since the definition of \( s_{f,q} \) is compatible with the product structure of the Milnor \( K \)-group, we may assume \( q = 2 \) and \( T_1 = X \). Since \( \{a, X\} \) is defined, by our convention, \( a \) can be written as \( a = 1 + bX \). The image of \( \{a, X\} \) under the symbol map \( K_2(B[1/X]) \rightarrow \hat{\Omega}^1_B[1/X]/d(B[1/X]) \) is \( p^{-1} \log(f(1+bX)/(1+bX)^p)dX/X \) which belongs to the image of \( \hat{\Omega}^1_B/dB \rightarrow \hat{\Omega}^1_B[1/X]/d(B[1/X]) \). This map is injective, so \( s_{f,2}(\{a, X\}) = p^{-1} \log(f(1+bX)/(1+bX)^p)dX/X \) (cf. also [10] 3.5).

Next we remark the assumption \( p > 2 \) is enough to show that \( s_{f,q} \) factors through \( K^M_q(A) \). In fact, by the compatibility of \( s_{f,q} \) with the product structure of the Milnor \( K \)-group, the problem again reduces to the case \( q = 2 \). So Chapter I Proposition (3.2) in [9] implies the desired property. We do not need the \( q \)-th divided power \( J^{[q]} \) or \( S_n(q) \) with \( q > 2 \) in [9] to see this.

We go back to the proof of Proposition A1.3. We have

\[ s_{f,q} \circ E_q(aX \cdot \frac{dT_1}{T_1} \wedge \ldots \wedge \frac{dT_{q-1}}{T_{q-1}}) = (f_1 - 1) \log \exp \left( \sum_{n=0}^{\infty} f_1^n(aX) \frac{dT_1}{T_1} \wedge \ldots \wedge \frac{dT_{q-1}}{T_{q-1}} \right) \]

\[ = -aX \cdot \frac{dT_1}{T_1} \wedge \ldots \wedge \frac{dT_{q-1}}{T_{q-1}}. \]

This means that \( s_{f,q} \circ E_q = -id \). Thus, \( E_q \) is injective.

On the other hand, by [2] (4.2) and (4.3), we have a surjective homomorphism

\[ \rho_i : \hat{\Omega}_B^{q-1} \oplus \hat{\Omega}_B^{q-2} \rightarrow U_X^i K^M_q(B)^\wedge /U_X^{i+1} K^M_q(B)^\wedge \]
such that

\[ \rho_i(\frac{a \ db_1}{b_1} \wedge \ldots \wedge \frac{db_{q-1}}{b_{q-1}}, 0) = \{1 + X^i a, b_1, \ldots, b_{q-1}\} \]

\[ \rho_i(0, \frac{a \ db_1}{b_1} \wedge \ldots \wedge \frac{db_{q-2}}{b_{q-2}}) = \{1 + X^i a, b_1, \ldots, b_{q-2}, X\} \]

where \( a \in B \), and \( b_i \in B^\times \). This shows that \( U^i_X K^M_q(B) / U^{i+1}_X K^M_q(B) \) is generated by the elements of the form \( \{1 + aX^i, T_1, \ldots, T_{q-1}\} \) where \( a \in B \), and \( T_1, \ldots, T_{q-1} \) are in \( I_B \). Hence, \( E_q \) is surjective, which completes the proof.

A.2. Smooth local rings over a ramified base.

A.2.1. In this section, we fix a ring \( B \) as in \( \S 1 \), and study a ring

\[ A = B / \mathfrak{I} \quad \text{where} \quad \mathfrak{I} = (X^e - pu) \]

Here, \( u \) is a unit of \( B \), and \( \mathfrak{I} \) is the ideal of \( B \) generated by \( X^e - pu \). We put \( \varphi = X^e - pu \). We denote by

\[ \psi : B \longrightarrow A \]

the canonical homomorphism. (For example, if \( A \) is a complete discrete valuation ring with mixed characteristics, one can take \( \Lambda \) as in \( \S \)A1 such that \( A/\Lambda \) is finite and totally ramified. Suppose that \( R = \Lambda, B = R[[X]] \), and \( f(X) = X^e - pu \) \( (u \in B^\times) \) is the minimal polynomial of a prime element of \( A \) over \( \Lambda \). Then, \( A \simeq B/(X^e - pu) \) and the above condition on \( A \) is satisfied.)

Let \( D \) be the divided power envelope of \( B \) with respect to the ideal \( \mathfrak{I} \), namely \( D = B[\varphi^r/r! : r > 0] \). We also denote by

\[ \psi : D \longrightarrow A \]

the canonical homomorphism which is the extension of \( \psi : B \longrightarrow A \).

We define \( J = \text{Ker}(D \xrightarrow{\psi} A) \). Then, the endomorphism \( f \) of \( B \) naturally extends to \( D \). Since \( \varphi = X^e - pu \), we have \( D = B[\varphi^r/r! : r > 0] = B[X^{er}/r! : r > 0] \). Hence, \( f(J) \subset pD \) holds. So \( f_1 = p^{-1}f : J \longrightarrow D \) can be defined. Since \( f(\hat{\Omega}^{aq-1}_B) \subset p^{aq-1}\hat{\Omega}^{aq-1}_B \), \( f_{q-1} = p^{-(q-1)}f \) can be defined on \( \hat{\Omega}^{aq-1}_B \), and

\[ f_q = \frac{1}{pq} f : J \otimes \hat{\Omega}^{aq-1}_B \longrightarrow D \otimes \hat{\Omega}^{aq-1}_B \quad (19) \]

can be also defined.
A.2.2. Recall that $B = R[[X]]$. We denote the image of $X$ in $A$ by the same letter $X$. For $i > 0$, we define $U_X^iA^\times = 1 + X^iA$. We note that $U_X^1A^\times$ is $p$-adically complete.

**Lemma A.2.1.** Let $e' = [e/(p-1)] + 1$ be the smallest integer $i$ such that $i \geq e/(p-1) + 1$. Then, $x \mapsto x^p$ gives an isomorphism
\[
U_X^{e'}A^\times \cong U_X^{e+e'}A^\times.
\]


For an element $x \in U_X^{e+e'}A^\times$, by Lemma A2.1, there is a unique $y \in U_X^{e'}A^\times$ such that $y^p = x$. We denote this element by $x^{1/p}$. By the same way, for $x \in U_X^{ne+e'}A^\times$, a unique element $y \in U_X^{e'}A^\times$ such that $y^{pn} = x$, is denoted by $x^{1/p^n}$. Since $U_X^1A^\times$ is a $\mathbb{Z}_p$-module, we also use the notation $x^{1/mp^n}$ for an integer $m$ with $(p, m) = 1$ for $x \in U_X^{ne+e'}A^\times$.

Recall that $D = B[\varphi^r/r! : r > 0] = B[X^er/r! : r > 0]$. Let $U_X^1D$ be the ideal of $D$ generated by all $X^er/r!$ with $r > 0$. We define a homomorphism
\[
E_{1,A} : U_X^1D \rightarrow A^\times
\]
by
\[
E_{1,A}(aX^er/r!) = \psi(E_1(aX^er))^{1/r!}
\]
where $a \in B$, and $E_1 : XB \rightarrow B^\times$ is the map defined in §A.1. Since $er \geq e \operatorname{ord}_p(r!) + e'$, $\psi(E_1(aX^er))^{1/r!}$ is well-defined by the above remark.

A.2.3. For $q > 0$, we will define $E_{q,A}$ similarly as in 1.3. For $i > 0$, let $U_X^1(D \otimes \hat{\Omega}_B^{q-1})$ (resp. $U_X^i(D \otimes \hat{\Omega}_B^{q-1})$) be the subgroup generated by $a \cdot (dT_1)/T_1 \wedge \ldots \wedge (dT_{q-1})/T_{q-1}$ where $a \in U_X^1D$ (resp. $a \in X^iD$) and $T_j \in I_B$.

Let $K_q^M(A)$ be the $q$-th Milnor $K$-group. As in 1.3, for $i \geq 0$, let $U_X^iK_q^M(A)$ be the subgroup generated by $\{1 + X^iA, A^\times, \ldots, A^\times\}$ and $\{1 + X^iA, A^\times, \ldots, A^\times, X\}$, and define $K_q^M(A)^\wedge$ to be the completion of $K_q^M(A)$ with respect to the filtration $U_X^iK_q^M(A)$. We denote by $U_X^iK_q^M(A)^\wedge$ the closure of $U_X^iK_q^M(A)$ in $K_q^M(A)^\wedge$. Note that $U_X^1K_q^M(A)^\wedge$ is $p$-adically complete, namely $U_X^1K_q^M(A)^\wedge = \lim\inf U_X^iK_q^M(A)/p^n$. We also note that by definition, a natural homomorphism $K_q^M(B)^\wedge \rightarrow K_q^M(A)^\wedge$ exists.

We define
\[
E_{q,A} : U_X^1(D \otimes \hat{\Omega}_B^{q-1}) \rightarrow K_q^M(A)^\wedge
\]
by
\[
E_{q,A}(a) \cdot \left(\frac{dT_1}{T_1} \wedge \ldots \wedge \frac{dT_{q-1}}{T_{q-1}}\right) = \{E_{1,A}(a), \psi(T_1), \ldots, \psi(T_{q-1})\}
\]
where $T_i \in I_B$. 

Recall that $f_q = p^{-q} f : J \otimes \hat{\Omega}_B^{q-1} \to D \otimes \hat{\Omega}_B^{q-1}$ is defined (cf. (19)). We put

$$S^q_f(A, B) = D \otimes \hat{\Omega}_B^{q-1}/(d(D \otimes \hat{\Omega}_B^{q-2}) + (f_q - 1)(J \otimes \hat{\Omega}_B^{q-1})).$$  \hspace{1cm} (21)

The filtration on $D \otimes \hat{\Omega}_B^{q-1}$ induces a filtration on $S^q_f(A, B)$, which we denote by $U^i X S^q_f(A, B)$. Our aim in this section is to prove

**Theorem A.2.2.** $E_{q,A}$ induces an isomorphism

$$E_{q,A} : U^1 X S^q_f(A, B) \xrightarrow{\sim} U^1 X K^M_q(A)^\wedge$$

which preserves the filtrations.

**A.2.4.** Let $\hat{\Omega}_A^{q-1}$ be the $p$-adic completion of $\Omega_A^{q-1}$. We begin with the following lemma.

**Lemma A.2.3.** There exists a homomorphism $\exp_p^2 : \hat{\Omega}_A^{q-1} \to K^M_q(A)^\wedge$ such that

$$a - a^{\wedge} \in \hat{\Omega}_A^{q-1}/d\hat{\Omega}_A^{q-2} \mapsto \{\exp(p^2a, b_1, ..., b_{q-1}) \mid a \in A, b_i \in A^x\}$$

where $a \in A$, $b_i \in A^x$, and $\exp(x) = \sum_{n \geq 0} x^n / n!$. Furthermore, $d\hat{\Omega}_A^{q-2}$ is contained in the kernel of $\exp_p^2$.

Proof. By Corollary 2.5 in [14], we have a homomorphism

$$\exp_p^2, B : \hat{\Omega}_B^{q-1}/d\hat{\Omega}_B^{q-2} \to K^M_q(B)^\wedge$$

such that

$$a - a^{\wedge} \in \hat{\Omega}_B^{q-1}/d\hat{\Omega}_B^{q-2} \mapsto \{\exp(p^2a, b_1, ..., b_{q-1}) \mid a \in B, b_i \in B^x\}$$

where $a \in B$ and $b_i \in B^x$. Consider the exact sequence

$$\hat{\Omega}_B^{q-1} \to \hat{\Omega}_B^{q-1}/d\hat{\Omega}_B^{q-2} \to \hat{\Omega}_A^{q-1}/d\hat{\Omega}_A^{q-2} \to 0.$$

Since $\hat{\Omega}_B^{q-1}$ is clearly in the kernel of $\psi \circ \exp_p^2, B : \hat{\Omega}_B^{q-1}/d\hat{\Omega}_B^{q-2} \to K^M_q(B)^\wedge \to K^M_q(A)^\wedge$, the map $\exp_p^2, B$ induces the desired homomorphism

$$\exp_p^2 : \hat{\Omega}_A^{q-1}/d\hat{\Omega}_A^{q-2} \to K^M_q(A)^\wedge.$$

**Corollary A.2.4.** For any $a \in A \setminus \{0\}$, in $K_2(A)^\wedge$ we have

1. $\{\exp(p^2a, a) = 0$,
2. $\{\exp(p^3a, p) = 0$. 

Proof. In the proof of Lemma 2.5 in [12], we showed that
\[ \{\exp(p^2a), a\} + \{\exp(p^2b), b\} = \{\exp(p^2(a + b)), a + b\}. \]
This formula holds for \( a, b \) such that \( a, b, a + b \in A \setminus \{0\} \), hence (1) is reduced to the case \( a \in A^\times \), so follows from Lemma A2.3.

The equation (2) is a consequence of (1). In fact,
\[ \{\exp(p^3a), a\} = p\{\exp(p^2a), a\} = 0 \]
by (1). So we have
\[ \{\exp(p^3a), p\} = \{\exp(p^3a), ap\}. \]
But the latter is zero again by (1).

A.2.5. We first show

**Lemma A.2.5.** \( E_{q,A} \) vanishes on \( d(U_X^1(D \otimes \hat{\Omega}_B^{q-2})) \).

As in Lemma A1.2, it suffices to show \( E_{2,A}(d(aX^{cr}/r!)) = 0 \) for \( a \in D \) and \( r \) such that \( f(a) = a^p \) and \( r \geq p \). Let \( E^{AH}(T) = \prod_{(p,m)=1}(1 - T^i)^{-\mu(m)/m} \in \mathbb{Z}_p[[T]] \) be the Artin-Hasse exponential. We have
\[
E_{2,A}(d(aX^{cr}/r!)) = \{\psi(E^{AH}(aX^{cr}))^{1/(r-1)!}, \psi(X^e)\} + \{\psi(E^{AH}(aX^{cr}))^{1/r!}, \psi(a)\}
\]
\[
= \{E^{AH}((p\psi(u))^r\psi(a))^{1/(r-1)!}, p\psi(u)\} + \{E^{AH}((p\psi(u))^r\psi(a))^{1/r!}, \psi(a)\}
\]
\[
= \{E^{AH}((p\psi(u))^r\psi(a))^{1/(r-1)!}, p\} + \{E^{AH}((p\psi(u))^r\psi(a))^{1/r!}, \psi(au^r)\}.
\]
Hence, Lemma A2.5 is reduced to show the following.

**Lemma A.2.6.** For any \( a \in A \setminus \{0\} \),
\begin{enumerate}
  \item \( E^{AH}(p^ra)^{1/(r-1)!}, p \) = 0,
  \item \( E^{AH}(p^ra)^{1/r!}, a \) = 0.
\end{enumerate}

Proof of Lemma A2.6. From \( E^{AH}(T) = \sum_{m=0}^{\infty} \exp(T^{pm}/p^m) \), in order to prove Lemma A2.6 (1), it is enough to show \( \{\exp((p^ra)^{pm}/p^m(r-1)!), p\} = 0 \), which follows from Corollary A2.4 (2). By the same method, Lemma A2.6 (2) follows from Corollary A2.4 (1).

By Lemma A2.5, \( E_{q,A} \) induces a homomorphism
\[
E_{q,A} : U_X^1(D \otimes \hat{\Omega}_B^{q-1})/d(U_X^1(D \otimes \hat{\Omega}_B^{q-2})) = U_X^1(D \otimes \hat{\Omega}_B^{q-1})/[U_X^1(D \otimes \hat{\Omega}_B^{q-1}) \cap d(D \otimes \hat{\Omega}_B^{q-2})] \rightarrow K^M_q(A)^\wedge.
\]
A.2.6. Next we have to show that $E_{q,A}$ vanishes on

$$
\text{Image}(J \otimes \hat{\Omega}_B^{q-1} \to D \otimes \hat{\Omega}_B^{q-1} \to D \otimes \hat{\Omega}_B^{q-1}/d(D \otimes \hat{\Omega}_B^{q-2}))
\cap U^1_X(D \otimes \hat{\Omega}_B^{q-1})/d(U^1_X(D \otimes \hat{\Omega}_B^{q-2})).
$$

We assume that

$$
\varpi = \sum_{r>0} \frac{(X^e - pu)^r}{r!} (\eta_r + X \omega_r)
$$

satisfies

$$
(f_q - 1)(\varpi) \in U^1_X(D \otimes \hat{\Omega}_B^{q-1}) \pmod{d(D \otimes \hat{\Omega}_B^{q-2})}
$$

where $\eta_r \in \hat{\Omega}_R^{q-1}$ and $\omega_r \in \hat{\Omega}_B^{q-1}$. We write $u = u_0 + u_1 X$ with $u_0 \in R^\times$ and $u_1 \in B$. We put

$$
\eta = \frac{1}{p} \sum_{r>0} \frac{(-pu_0)^r}{r!} \eta_r.
$$

So $\varpi - p\eta \in U^1_X(D \otimes \hat{\Omega}_B^{q-1})$. The assumption (23) implies that

$$
(f_q - 1)(p\eta) \in d(\hat{\Omega}_R^{q-2}).
$$

Lemma A.2.7. $\eta$ can be written as $\eta = p\eta_1$ such that $\eta_1 \in d(\hat{\Omega}_R^{q-2})$.

By the standard method, Lemma A2.7 is obtained from (24) (cf. [6] Chap.0 Corollaire 2.3.14).

We put

$$
\varpi_1 = \sum_{r>0} \frac{(X^e - pu)^r}{r!} - \frac{(-pu_0)^r}{r!} \eta_r, \quad \varpi_2 = \sum_{r>0} \frac{(X^e - pu)^r}{r!} X \omega_r.
$$

So by (22),

$$
\varpi = \varpi_1 + \varpi_2 + p\eta.
$$

From (24) and the definition of $E_{q,A}$, we have

$$
E_{q,A}((f_q - 1)\varpi) = E_{q,A}((f_q - 1)\varpi_1) + E_{q,A}((f_q - 1)\varpi_2).
$$

If we write $\omega_r = \Sigma_{i} a_{r,i}(dT_{r,i,1})/T_{r,i,1} \wedge \ldots \wedge (dT_{r,i,q-1})/T_{r,i,q-1}$ with $T_{r,i,j} \in I_B$, by the definition of $E_{q,A}$,

$$
E_{q,A}((f_q - 1)\varpi_2) = \sum_{r,i} \{ \psi(\exp(\frac{(X^e - pu)^r}{r!} X a_{r,i})), \psi(T_{r,i,1}), \ldots, \psi(T_{r,i,q-1}) \}
$$

$$
= 0.
$$

Next we calculate $E_{q,A}((f_q - 1)\varpi_1)$. We write $\eta_r = \Sigma_{i} b_{r,i}(dT_{r,i,1})/T_{r,i,1} \wedge \ldots \wedge (dT_{r,i,q-1})/T_{r,i,q-1}$ with $T_{r,i,j} \in I_B$. Then by the definition of $E_{q,A}$, we
get
\[E_{q,A}((f_q - 1)\varpi_1) = \sum_{r,i} \{\psi \exp\left(\frac{(X^e - pu)^r}{r!} b_{r,i}\right), \psi(T_{r,i,1}), ..., \psi(T_{r,i,q-1})\}\]

By Lemma A2.7,
\[\sum_{r>0} \frac{(-pu_0)^r}{r!} \eta_r = p\eta = p^2 \eta_1\]
and \(\eta_1 \in d(\hat{\Omega}^{q-2}_R)\). Hence by Lemma A2.3,
\[E_{q,A}((f_q - 1)\varpi_1) = -\exp p^2(\eta_1) = 0.\]

This shows that
\[\text{Image}(J \otimes \hat{\Omega}^{q-1}_B f_q^{-1} F_q^{-1} D \otimes \hat{\Omega}^{q-1}_B \longrightarrow D \otimes \hat{\Omega}^{q-1}_B / d(D \otimes \hat{\Omega}^{q-2}_B))\]
\[\cap [U^1_X(D \otimes \hat{\Omega}^{q-1}_B) / d(U^1_X(D \otimes \hat{\Omega}^{q-2}_B))]
\]
is in the kernel of \(E_{q,A}\). Namely, \(E_{q,A}\) induces a homomorphism
\[E_{q,A} : U^1_X S_q^f(A, B) \longrightarrow U^1_X K^M_q(A) \wedge.\] (26)

A.2.7. As in §1, \(E_{q,A}\) has the inverse. The target group of the symbol map in [9] has two components as in §1, and its projection to the first component is
\[s_{f,q,A} : K^M_q(A) \longrightarrow S_q^f(A, B)\]
which satisfies
\[s_{f,q,A}(\{a_1, ..., a_q\})\]
\[= \sum_{i=1}^q (-1)^{i-1} \frac{1}{p} \log f(\tilde{a}_i) d\tilde{a}_1 \wedge ... \wedge d\tilde{a}_{i-1} \wedge f\left(\frac{d\tilde{a}_{i+1}}{\tilde{a}_{i+1}}\right) \wedge ... \wedge f\left(\frac{d\tilde{a}_q}{\tilde{a}_q}\right)\]
where \(\tilde{a}_i\) is an element of \(D^\times\) such that \(\psi(\tilde{a}_i) = a_i\). This does not depend on the choices of \(\tilde{a}_i\).

As in §1, \(s_{f,q,A} \circ E_{q,A} = -id\) because if \(T_1, ..., T_{q-1}\) are in \(I_B\), then
\[s_{f,q}(\{a, \psi(T_1), ..., \psi(T_{q-1})\}) = \frac{1}{p} \log \frac{f(\tilde{a})}{\tilde{a}} dT_1 / T_1 \wedge ... \wedge dT_{q-1} / T_{q-1}.\]

(As we note in §A1, we are allowed to take \(T_i = X\) using our convention.) So \(E_q\) is injective. On the other hand, by considering \(U^i_X K^M_q(A) / U^{i+1}_X K^M_q(A)\) as in §A1, we know that \(E_q\) is surjective. Hence, \(E_q\) is bijective. It is clear that \(E_q\) preserves the filtrations. This completes the proof of Theorem A2.2.
Remark A.2.8. By a slight modification, we can deal with more general ring, for example, a ring of the form $R[X_1, \ldots, X_r]_{(m_R, x_1, \ldots, x_r)}/(X_1^{e_1} \cdot \ldots \cdot X_r^{e_r} - pu)$ by the same method.

Remark A.2.9. Assume that $\# I \leq q - 2$. Then we have $U_1^1 S_q^q(A, B) = S_q^q(A, B)$ and $U_1^1 K_q^M(A)^\wedge = K_q^M(A)^\wedge$. So Theorem 1.1 says that we have an isomorphism

$$E_{q, A} : S_q^q(A, B) \simeq K_q^M(A)^\wedge.$$ 

This isomorphism in this special case was obtained in Kato [10].

Corollary A.2.10. There exists a homomorphism

$$\exp_p : \Omega_A^{q-1} \longrightarrow K_q^M(A)^\wedge$$

such that

$$a \frac{db_1}{b_1} \wedge \ldots \wedge \frac{db_{q-1}}{b_{q-1}} \mapsto \{\exp(pa), b_1, \ldots, b_{q-1}\}$$

where $a \in A$ and $b_i \in A^\times$.

Proof. By [2] Lemma 4.2, it suffices to show

$$\sum_{i=1}^l \{\exp(pa_i), a_i, b_1, \ldots, b_{q-2}\} = \sum_{i=1}^m \{\exp(pa'_i), a'_i, b_1, \ldots, b_{q-2}\} \quad (27)$$

for $a_i, a'_i, b_j \in A^\times$ such that $\Sigma a_i = \Sigma a'_i$. So we may assume $q = 2$.

Let $s_{f, 2, A}$ be the map as above. Then, for $a \in A^\times$, taking $a \in B$ such that $\psi(\tilde{a}) = a$, we can calculate

$$s_{f, 2}\{\exp(pa), a\} = (f_1 - 1) \log \exp(p\tilde{a}) f_1(d \log \tilde{a}) - \frac{1}{p} \log(f(\tilde{a})/\tilde{a}^p) d \log \exp(p\tilde{a}) = f_1(d\tilde{a}) - pd\tilde{a}.$$

Here, we used $d(\log(f(\tilde{a})/\tilde{a}^p) \cdot \tilde{a}) = 0$ in $S_q^q(A, B)$. The final equation is clearly additive in $a$. Since

$$s_{f, 2, A} : U_1^1 K_2^M(A)^\wedge \longrightarrow U_1^1 S_q^q(A, B)$$

is bijective by Theorem A2.2, $\{\exp(pa), a\}$ is additive in $a$, and (27) is satisfied. Hence, $\exp_p$ is a homomorphism.

Remark A.2.11. One has $\{\exp(p\tilde{a}bX^i), \tilde{b}X^i\} = \{\exp(p\tilde{a}(1 + \tilde{b}X^i)), (1 + \tilde{b}X^i)\}$ for $i > 0$, $\tilde{a} \in B$, and $\tilde{b} \in B^\times$ (note that $\{\exp(p\tilde{a}bX^i), \tilde{b}X^i\}$ makes sense in $K_2(B)^\wedge$ by our convention (cf.1.3)) because $s_{f, 2}\{\exp(p\tilde{a}bX^i), \tilde{b}X^i\}$
\( = s_{f,2}(\{\exp(p\tilde{a}(1+\tilde{b}X^i)), (1+\tilde{b}X^i)\}) \) (cf. remark after the definition of \( s_{f,q} \) in the proof of Proposition A1.3). Hence, we have

\[
\exp_p(ab_1X^i \wedge db_2 \wedge ... \wedge db_{q-1}) = \{\exp(pab_1X^i), b_1X^i, b_2, ..., b_{q-1}\}
\]

for \( a \in A, b_1, ..., b_{q-1} \in A^\times, \) and \( i > 0. \)

**Remark A.2.12.** Theorem 1.1 gives a different proof of the main result in [13]. Let \( K \) be a complete discrete valuation field with integer ring \( O_K, \) and \( X \) be a smooth scheme over \( O_K. \) We denote by \( i : Y \to X \) the special fiber of \( X \) and by \( j : X_\eta \to X \) the generic fiber of \( X. \)

Let \( K^M_q(O_X) \) be the sheaf of Milnor \( K \)-groups, and \( S_n(r) \) be the syntomic complex on \( D(Y_{et}) \) defined in [9] for \( n > 0. \) Then by using (a modified version of) Theorem A2.2, we can show the existence of an isomorphism

\[
i^*K^M_q(O_X)/p^n \simeq \mathcal{H}^q(S_n(q)) \tag{28}
\]

for \( q \) such that \( 0 < q < p - 1. \) In fact, Theorem A2.2 says that \( U^1i^*K^M_q(O_X)/p^n \simeq U^1\mathcal{H}^q(S_n(q)). \) (Here \( U^1i^*K^M_q(O_X) \) is defined similarly as above.)

Comparing this isomorphism (28) with a result in [2], we have an exact sequence

\[
0 \to \mathcal{H}^q(S_n(q)) \to i^*R^qj_*\mathbb{Z}/p^n(q) \to W_n\Omega^{q-1}_{Y,\log} \to 0. \tag{29}
\]

This exact sequence was proved in [13] by a different method.

For \( r \) such that \( q < r < p - 1, \) we can also prove the bijectivity of

\[
i^*K^M_q(O_X)/p \otimes \mu_p^{\otimes(r-q)} \simeq \mathcal{H}^q(S_1(r)) \tag{30}
\]

by a similar method as in this paper. Then by (29), (30), and the theory of Fontaine and Messing, we can show the existence of a distinguished triangle

\[
S_n(r) \to \tau_{\leq r}i^*Rj_*\mathbb{Z}/p^n(r) \to W_n\Omega^{q-1}_{Y,\log}[-r]
\]

which was the main theorem of [13]. Tsuji extended this result to much more general setting [20] [21], and proved the semi-stable conjecture by Fontaine and Jannsen.

(*) **Note.** This paper was written long time ago, but the author still thinks the problems to determine all \( gr^iK^M_q(K) \) for complete discrete valuation fields of mixed characteristics, and also to determine the kernels of the exponential homomorphisms for Milnor \( K \)-groups (cf. [15]) are interesting problems.
References


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